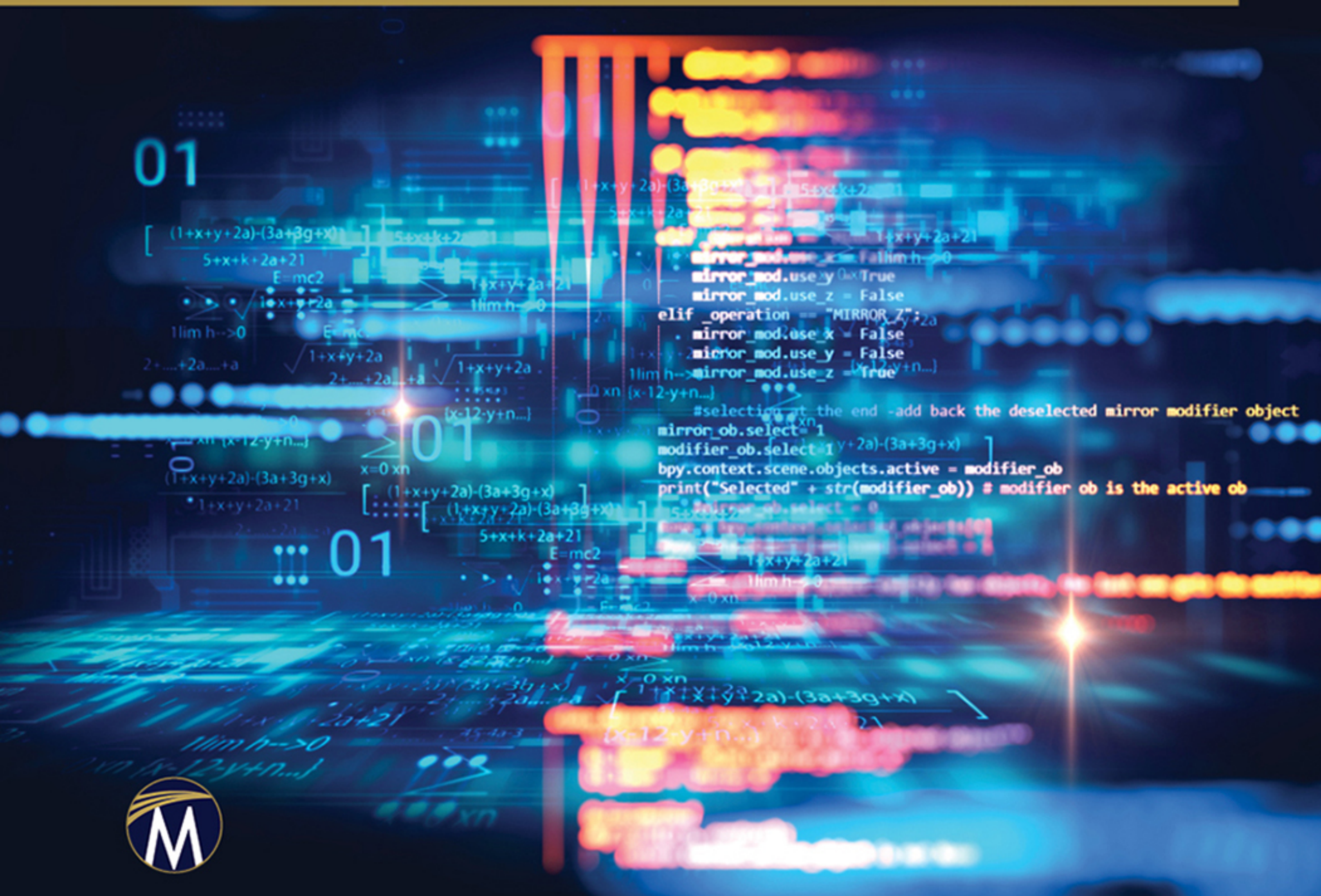
PYTHON

An Introduction To Programming

SECOND EDITION



JAMES R. PARKER

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Second Edition

Python

An Introduction to Programming

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Contents

Preface

Welcome to the second edition! This is a book that is intended to be used to teach programming to introductory students. There is material here for intro CS, but also for Science and other disciplines. I still believe that programming is an essential skill for all professionals and especially academics in the 21st century and I have tried to make that clear in the contents of this book.

There are two new chapters and some seriously revised ones. First, the book exclusively uses the Pygame library. The Glib module has been updated but is no longer used in this book. This means that Chapters 7, 9, and 12 are quite different from those in the previous edition. Also, Pygame no longer supports video, so rather than build a new module from scratch, video is not discussed.

The new Chapter 14 concerns *parsing*. This can be a more advanced topic, but parsing is a good thing to know about for many reasons, not the least of which is to deal with user input effectively. The main example is a programming language for which a parser (and compiler) will be written. The language was developed for this book and is called *PyJ*: it is a small subset of the *Julia* language, which in turn is a variation on Python designed for efficiency.

The new Chapter 15 involves graphical input. Here a paint-type program will be developed, so as to clarify ideas in mouse input and graphical output. The resulting program (*Mondrean*) is actually usable for making drawings.

I use a "just-in-time" approach, meaning that I try to present new information just before or just after the reader needs it. As a result, there are a lot of examples, and those examples were carefully selected to fit into the place they reside in the text. Not too soon, and not too late.

I believe in object-oriented programming. My master's thesis in the late 1970s was on that subject, and I cut my teeth on Simula, was there when C++ was created, and knew the creator of Java. I do not believe that object-oriented programming is the only solution, though, and realized early that good objects can only be devised by someone who can already program. I am therefore not an "objects first" teacher. I am a "whatever works best" teacher.

A lot of my examples involve games. That's because undergraduate students play games. They understand them better than, say, accounting or inventory systems, which have been typical early assignments. I believe in presenting students' assignments that are interesting. Not all students like games, and certainly not computer games, but a large number do. And they come to a game assignment with prior knowledge of the genre.

I have taught computer science for 26 years, and then moved to the arts. That's because of many things, but my experience teaching in a Drama department and more recently in the Art department has helped me immensely in understanding the role of computing and programming in general. I strongly feel that every student in a university should know how to write, and know how to program a computer. If you can't understand the computer, you are at the whim of programmers who, unseen in downtown high-rises and basements, who dictate how the world will work by default. The (sometimes poor) design decisions made, and the lack of attention paid to human needs results in actual policy being formed, and that is simply wrong. It's not always true that the code is bad, but when it is, it can have far reaching consequences.

Here is a truth: *nobody wants to run your program*. What they want is to get their work done, or play their game, or send their email. If you are an excellent programmer then you will enable that, and nobody will know your name. But nobody will curse your code either. The truth is that good code is invisible. It simply allows things to flow smoothly. Bad code is memorable. It interferes, makes people frustrated and angry. If you believe in karma, then I know what you would prefer.

You see, software (any computer program) is ubiquitous. Cars, phones, fridges, television, and almost everything in our society is computerized. Decisions made about how a program is to be built tend to live on, and even after many modifications can affect how people use that device or system. Creating good software means making a productive and happy civilization. It sounds trite, but if you think about it I'm sure you will agree.

Python is a great language for beginning programmers. It is easy to write the first programs, because the conceptual overhead is small. That is, there's no need to understand what 'void' or 'public' means at the outset. Python does a lot of things for a programmer. Do you want something sorted? It's a part of the language. Lists and hash tables (dictionaries) are a part of the language. You can write classes, but do not have to, so it can be taught *objects first* or not. The required indentation means that it is much harder to place code incorrectly in loops or if statements. There are hundreds of reasons why Python is a great idea.

And it is free. This book was written using Python version 3.4, and with the *PyCharm* API. The modules used that require download are few, but include PyGame and tweepy. All free.

Overview of Chapters

Here's a breakdown of the book, for instructors. It can be used to teach computer science majors or science students who wish to have a competency in programming.

Chapter 0: Historical and technological material on computers. Binary numbers, the fetch-execute cycle. This chapter can be skipped in some syllabi.

Chapter 1: Problem solving with a computer; breaking a problem down so it can be solved. The Python system. Some simple programs involving games that introduce variables, expressions, print, types, and the **if** statement.

Chapter 2: Repetition in programming: **while** and **for** statements. Random numbers. Counting loops, nested loops. *Drawing a histogram*. Exceptions (**try-except**)

Chapter 3: Strings and string operations. Tuples, their definition, and use. Lists and list comprehension. Editing, slices. The *bytes* type. And set types. Example: the game of *craps*.

Chapter 4: Functions: modular programming. Defining a function, calling a function. Parameters, including default parameters, and scope. Return values.

Recursion. *The Game of Sticks*. Variable parameter lists, assigning a function to a variable. Find the maximum of a mathematical function. Modules. *Game of Nim*.

Chapter 5: Files. What is a file and how are they represented? Properties of files. File exceptions. Input, output, append, **open**, **close**. Comma separated value (CSV) files. Game of *Jeopardy*. The **with** statement.

Chapter 6: Classes and object orientation. What is an object and what is a class? Types and classes. Python class structure. Creating instances, **__init__** and **self**. Encapsulation. Examples: *deck of playing cards*; a *bouncing ball*; *Cat-a-pult*. Designing with classes. Subclasses and inheritance. Video game objects. Duck typing.

Chapter 7: Graphics. The *Pygame* module. Drawing window; color representation, pixels. Drawing lines, curves, and polygons. Filling. Drawing text. Example: *Histogram*, *Pie chart*. Images and image display, getting and setting pixels. *Thresholding*. Generative art.

Chapter 8: Data and information. Python dictionaries. *Latin to English translator*. Arrays, formatted text, formatted input/output. *Meteorite landing data*. Non-text files and the *struct* module. *High score file* example. Random access. Image and sound file types.

Chapter 9: Digital media: Using the mouse and the keyboard. Animation. *Space shuttle control console* example. Transparent colors. Sound: playing sound files, volume, pause. Pygame module for sound.

Chapter 10: Basic algorithms in computer science. Sorting (selection, merge) and searching (linear, binary). Timing code execution. Generating random numbers; cryptography; data compression (including Huffman codes and RLE); hashing.

Chapter 11: Programming for Science. Roots of equations; differentiation and integration. Optimization (minimum and maximum) and curve fitting (regression). Evolutionary algorithms. Longest common subsequence or edit distance.

Chapter 12: Writing *good* code. A walk through two major projects: a word processor written as procedural code and a *breakout* game written as object-oriented code. A collection of effective rules for writing good code.

Chapter 13: Dealing with real world interfaces, which tend to be defined for you. Examples are Email (send and receive), FTP, inter-process communication (client-server), Twitter, calling other languages like C++.

Chapter 14: Parsing. Introduction to grammars and BNF. Parsing data. A small compiler for a small language.

Chapter 15: Graphical Interaction. Using the mouse in complicated ways. Drawing, erasing, modifying images.

Chapter Coverage for Different Majors

A **computer science** introduction could use most chapters, depending on the background of the students, but Chapters 0, 7, 9, and / or 11 could be omitted.

An **introduction to programming for science** could omit Chapters 0, 10, and 12.

Chapter 13 is always optional, but is interesting as it explains how social media software works under the interface.

Basic **introduction to programming for non-science** should include Chapters 0, 1, 2, 3, 4, 5, and 7.

Companion Files *(A disc is included in the physical book or files are available for downloading from the publisher by writing to info@merclearning.com.)*

The accompanying disc contains useful material for each chapter.

- Selected exercises are solved, including working code when that is a part of the solution.
- All significant examples are provided as Python code files, which can be compiled and executed, and can be modified as exercises or class projects. This includes sample data files when appropriate.
- All figures are available as images, in full color.

Instructor Ancillaries

- Solutions to almost all of the programming exercises given in the text.
- MS PowerPoint *lectures* provided for an entire semester (35 files) including some new examples and short videos.

- All of the Python code that appears in the books has been executed, and all complete programs are provided as .py files. Some of the numerous programming examples (over 100) that are explored in the book and for which working code is included:
  - ***An interactive breakout game***
  - ***The Game of Nim***
  - ***A text formatting system***
  - ***Plotting histograms and pie charts***
  - ***Reading Twitter feeds***
  - ***Play*** Jeopardy ***Using a CSV Data Set***
  - ***Sending and receiving Email***
  - ***A simple Latin to English translator***
  - ***Cryptography***
  - ***Rock-Paper-Scissors***
- Hundreds of answered multiple choice quiz and sample *examination questions* in MS Word files that can be edited and used in various ways.

Dedicated Website

Please consider contributing material to the on-line community at *https://sites.google.com/site/pythonparker/* and do have fun. If you don't then you're doing it wrong.

J. Parker
February 2021

Chapter 0

Modern Computers

In this chapter

Humans are tool makers and tool users. This is not unique in the animal kingdom, but the facility that humans have with tools and the variety of applications we have for them does make us unique. Starting with mechanical tools (*machines*) like levers and wheels that could lighten the physical effort of everyday life, more and more complex and specific devices have been created to assist with all facets of our lives. This was extended in the twentieth century to assisting with mental efforts, specifically calculation.

Computers are devices that humans have built to facilitate complex calculations. Early computers were used to do some of the computations needed to design the first nuclear bombs, but now computers seem to be everywhere, embedded within cars and kitchen appliances, and even with our own bodies. The success of these devices in such a wide range of application areas is a result of their ability to be *programmed* – that is, the device itself is only a potential when first built and has no specific function. It is designed to be configured to do any task that requires calculations, and the configuring process is what we call *programming*.

To some extent, this has taken the place of a lot of other tool development that used to be done by engineers. When designing a complex machine like an automobile, for example, there used to be a lot of mechanical work involved. The careful timing of the current to the spark plug was accomplished by rotating shafts with sensors, and resulted in the firing of each cylinder at the correct moment. The air to gasoline mixture fed into the engine was controlled by tubes and cables and springs. Now all of these things are done using computers that sense electric and magnetic events, do calculations, and send electrical control signals to actuators in the engine. The same computer can be used to control a refrigerator, make telephone calls on a cellular phone, change channels on a television, and wake you up in the morning. It is the flexibility of the computer that has led to them becoming a dominant technology in human society, and the flexibility comes largely from their ability to be programmed.

0.1 CALCULATIONS BY MACHINE

People have been calculating things for thousands of years and have always had mechanical aids to help.

When someone programs a computer, they are really communicating with it. It is an imperative and precise communication. *Imperative*, because the computer has no choice; it is being told what to do and will do exactly that. *Precise*, because a computer does not apply any interpretation to what it is being told. Human languages are vague and subject to interpretation and ambiguity. There are sentences that are legal in terms of syntax, but have no real meaning: “Which is faster, to Boston or by bus?” is a legal sentence in English that has no meaning. Such vagaries are not possible in a computer language. Computers do not *think* and so can’t evaluate a command that would amount to “expose the patient to a fatal dose of radiation” with any skepticism. As a result, we, as programmers, must be careful and precise in what we instruct the machine to do.

When humans communicate with each other, we use a language. Similarly, humans use languages to communicate with computers. Such languages are artificial (humans invented them for this purpose, all at once), terse (there are few, if any modifiers, and no way to express emotions or graduations of any feeling), precise (each item in the language means one thing), and written (we do not speak to the computer in a programming language).

Computer languages operate at a high level and do not represent the way the computer actually works. There are a few fundamental things that need to be known about computers. It's not required to know how they operate electronically, but there are basic principles that should be understood to put the process of using computers in a practical context.

0.2 HOW COMPUTERS WORK AND WHY WE MADE THEM

The reason people use computers is different depending on the point in history in which one looks, but the military always seems to be involved. There have been many calculating devices built and used throughout history, but the first one that would have been *programmable* was designed by Charles Babbage. The military, as well as the mathematicians of the day, were interested in more accurate mathematical tables, such as those for logarithms. At the time, these were calculated by hand, but the idea that a machine could be built to compute more digits of accuracy was appealing. This would have been a mechanical device of gears and shafts, but it was not completed due to budget and contracting issues.

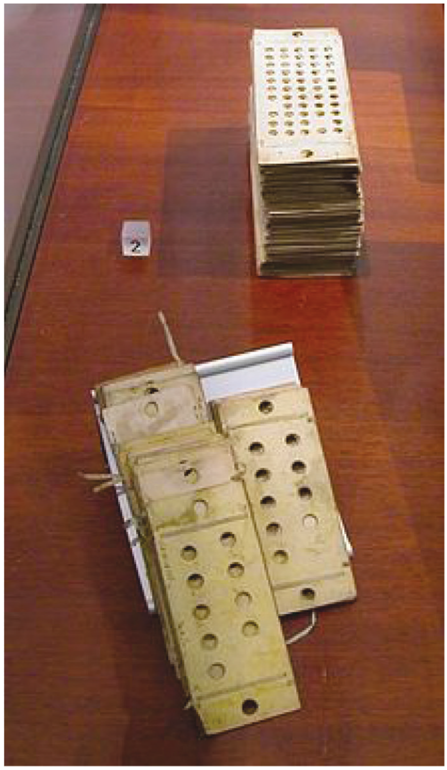


Figure 0.1
Punched cards for the Analytical Engine.

Babbage continued his work in design and created, on paper, a programmable mechanical device called the *analytical engine* in 1837. What does *programmable* mean? A calculation device is manipulated by the operator to perform a sequence of operations: add this to that, then subtract this and divide by something else. On a modern calculator, this would be done using a sequence of key presses, but on older

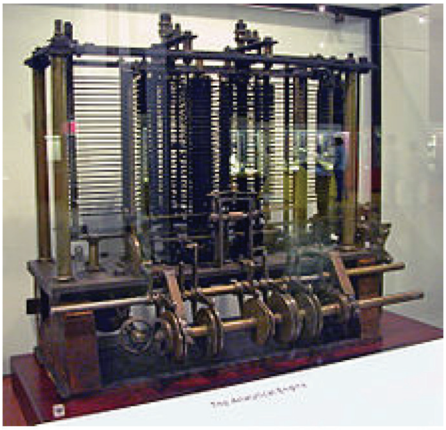


Figure 0.2
A portion of Babbage's Analytical Engine

devices, it may involve moving beads along wires or rotating gears along shafts. Now imagine that the sequence of key presses can be encoded on some other media: a set of cams, or plugs into sockets, or holes punched into cards. This is a *program*.

Such a set of punched cards or cams would be similar to a set of instructions written in English and given to a human to calculate, but would instead be coded in a form (*language*) that the computing device could use immediately. The directions on the cards could be changed so that something new could be computed as needed. The difference engine only found logarithms and trigonometric functions, but a device that could be programmed in this way could, in theory, calculate anything. The analytical engine was programmed by punching holes in stiff cards, an idea that was derived from the Jacquard loom of the day. The location of holes indicated either an operation (e.g., add or subtract) or data (a number). A sequence of such cards was executed one at a time and yielded a value at the end.

Although the analytical engine was never completed, a program was written for it, but not by Babbage. The world's first programmer may have been a woman, Augusta Ada King, Countess of Lovelace. She worked with Babbage for a few years and wrote a program to compute Bernoulli numbers. This was the first algorithm ever designed for a computer and is often claimed to be the first computer program ever written, although it was never executed.

The concept of *programmability* is a more important development than is the development of analytical engines. The idea that a machine can be made to do different things depending on a user-defined set of instructions is the basis of all modern computers, while the use of mechanical calculation has become obsolete; it is too slow, expensive, and cumbersome. This is where it began, though, and the concept of programming is the same today.

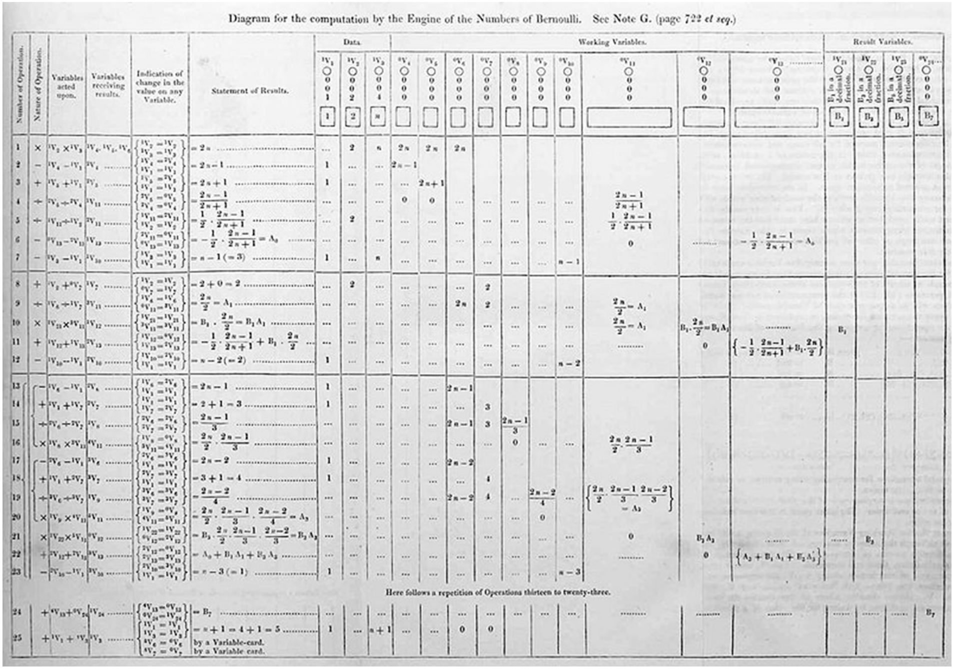


Figure 0.3
Possibly the word's first program: The calculation of Bernoulli numbers on the analytical engine.

During World War II, computers were run using electricity. Work on breaking codes and building the atomic bomb required large amounts of computing. Initially, some of this was provided by rooms full of humans operating mechanical calculators, but they could not keep up with the demand, so electronic computers were designed and built. The first was Colossus, designed and built by Tommy Flowers in 1943. It was created to help break German military codes, and an updated version (Mark II) was built in 1944.

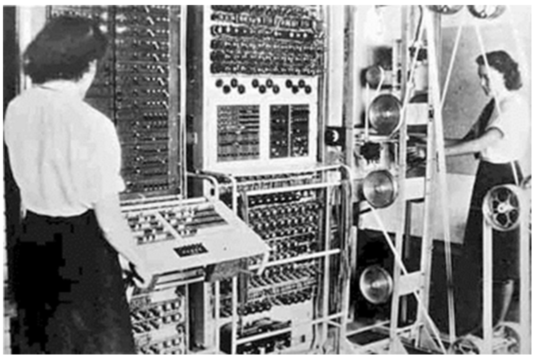


Figure 0.4
The Colossus computer breaking a code during World War II with the help of Dorothy Du Boisson (left) and Elsie Booker

In the United States, there was a need for computational power in Los Alamos when the first nuclear weapons were being built. Electro-mechanical calculators were replaced by IBM punched-card calculators, originally designed for accounting. These were only a little faster than the humans using calculators, but could run twenty-four hours a day and made fewer errors. The punch-card computer was programmed by plugging wires into sockets to create new connections between components.

0.2.1 Numbers

The electronic computers described so far, and those of the 1940s generally, had almost no storage for numbers. Input was through devices like cards, and they had numbers on them. They were transferred to the computation unit, then moved ahead or back, and perhaps read again. Memory was a primitive thing, and various methods were devised to store just a few digits. A significant advance came when engineers decided to use binary numbers.

Electronic devices use current and voltage to represent information, such as sounds or pictures (radio and television). One of the simplest devices is a switch, which can open and close a circuit and turn things like lights on and off. Electricity needs a complete circuit or route from the *source* of electrons, the negative pole of a battery perhaps, to the *sink*, which could be the positive pole. Electrons, which is what electricity is, in a simple sense, flow from the negative to the positive poles of a battery. Electricity can be made to do work by putting devices in the way of the flow of electrons. Putting a lamp in the circuit can cause the lamp to light up, for example.

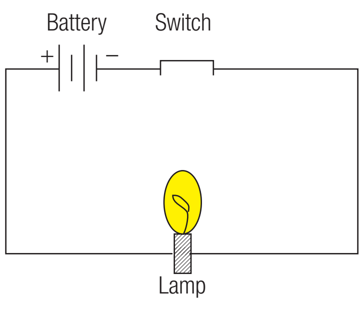


Figure 0.5
The switch is closed and the current is flowing, turning the lamp on. This is a "1."

A switch makes a break in the circuit, which stops the electrons from flowing; they cannot jump the gap. This causes the lamp to go dark. This seems obvious to anyone with electric lights in their house, but what may not be so obvious is that this creates two states of the circuit, *on* and *off*. These states can be assigned numbers. Off is 0, for example, and on is 1. This is how most computers represent numbers: as on/off or 1/0 states. Let's consider this in regards to the usual way we represent numbers, which is called *positional numbering*.

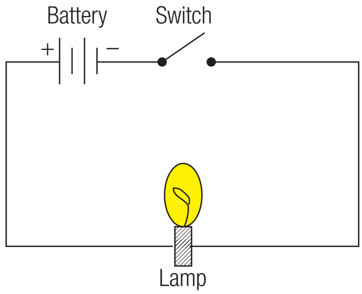


Figure 0.6
The switch is off (open) and the lamp is off, indicating a "0."

Most human societies now use a system with ten digits: 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. The number 123 is a combination of digits and powers of ten. It is a shorthand notation for 100 + 20 + 3, or $1 \times 10^2 + 2*10^1 + 3*10^0$. Each digit is multiplied by a power of ten and summed to get the value of the number. Anyone who has been to school accepts this and does not think about the value used as the basis of the system: ten. It simply happens to be the number of digits humans have on their hands. Any base would work almost as well.

Example: Base 4

Numbers that use 4 as a base can only have the digits 0, 1, 2, and 3. Each position in the number represents a power of 4. Thus, the number 123 is, in base 4, $1 \times 4^2 + 2*4^1 + 3*4^0$, which is $1 \times 16 + 2*4 + 3 = 16 + 8 + 3 = 27$ in traditional base 10 representation.

This could get confusing, what with various bases and such, so the numbers here are considered to be in base 10 unless specifically indicated otherwise by a suffix. For example, 123_4 is 123 in base 4, whereas 123_8 is 123 in base 8.

Binary numbers can have digits that are 1 or 0. The numbers are in base 2, and can therefore only have the digits 0 and 1. These numbers can be represented by the on/off state of a switch or *transistor*, an electronic switch, which why they are used in electronic computers. Modern computers represent all data as binary numbers because it is easy to represent those numbers in electronic form; a voltage is arbitrarily assigned to "0" and to "1." When a device detects a particular voltage, it can then be converted into a digit, and vice-versa. If 2 volts is assigned to a 0, and 5 volts is assigned to a 1, then the circuit shown in Figure 0.7 could signal a 0 or 1, depending on what switch was selected.

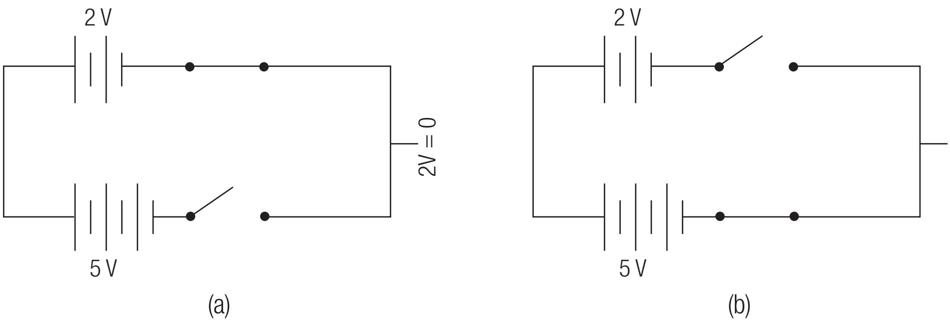


Figure 0.7
(a) A configuration giving a 2-volt value, or a zero.
(b) A configuration giving a 5-volt value, or a one.

Convert Binary Numbers to Decimal

Consider the binary number 11011_2. The subscript "2" here means "base 2." It can be converted into base 10 by multiplying each digit by its corresponding power of two and then summing the results.

Digit	1	1	0	1	1
Position	4	3	2	1	0
Power of 2	$2^4 = 16$	$2^3 = 8$	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$
Digit*power	16	8	0	2	1
Sum is $16 + 8 + 2 + 1 = 27_{10}$					

Some observations:

- Terminology: A digit in a binary number is called a *bit* (for **b**inary dig**it**)
- Any even number has 0 as the low digit, which means that odd numbers have 1 as the low digit.
- Any exact power of two, such as 16, 32, 64, and so on, will have exactly one digit that is a 1, and all others will be 0.
- Terminology: A binary digit or bit that is 1 is said to be *set*. A bit that is 0 is said to be *clear*.

Convert Decimal Numbers to Binary

Going from base 10 to base 2 is more complicated than the reverse. There are a few ways to do the calculation, but here's one that many people find easy to understand. If the lowest digit (rightmost) is 1, then the number is odd, and otherwise it is even. If the number 73_{10} is converted into binary, the rightmost digit is 1, because the number is odd.

The next step is to divide the number by 2, eliminating the rightmost binary digit, the one that was just identified, from the number. $73_{10}/2_{10} = 36_{10}$, and there can be no fractional part so any such part is to be discarded. Now the problem is to convert = 36_{10} to binary and then append the part already converted to that. Is 36_{10} even or odd? It is even, so the next digit is 0. The final two digits of 73_{10} in binary are 01.

The process is repeated:

Divide 36 by 2 to get 18, which is even, so the next digit is 0.

Divide 18 by 2 to get 9, which is odd, so the next digit is 1.

Divide 9 by 2 to get 4, which is even, so the next digit is 0.

Divide 4 by 2 to get 2, which is even, so the next digit is 0.

Divide 2 by 2 to get 1, which is odd, so the next digit is 1.

Divide 1 by 2 to get 0. When the number becomes 0, the process is complete.

The conversion process gives the binary numbers in reverse order (right to left) so the result is that $73_{10} = 1001001_2$.

Is this correct? Convert this binary number into decimal again:

$$1001001_2 = 1 \times 2^0 + 1*2^3 + 1*2^6 = 1 + 8 + 64 = 73_{10}.$$

A summary of the process for converting x into binary for is as follows:

```
Start at digit n=0 (rightmost)
repeat
   If x is even, the current digit n is 0 otherwise it is 1.
    Divide x by 2
    Add 1 to n
    If x is zero then end the repetition
```

Arithmetic in Binary

Computers do all operations on data as binary numbers, so when two numbers are added, for example, the calculation is performed in base 2. Base 2 is easier than base 10 for some things, and adding is one of those things. It's done in the same way as in base 10, but there are only 2 digits, and twos are carried instead of tens. For example, let's add 01011_2 to 01110_2:

```
0 1 0 1 1₂
0 1 1 1 0₂
```

Starting the sum on the right as usual, there is a 0 added to a 1 and the sum is 1, just as in base 10.

```
0 1 0 1 1₂
0 1 1 1 0₂
----------
        1₂
```

The next column in the sum contains two 1s. 1 + 1 is two, but in binary that is represented as 10_2. So, the result of 1+1 is 0 with a carry of 1 is as follows:

```
    1
0 1 0 1 1₂
0 1 1 1 0₂
----------
      0 1₂
```

The next column has 1 + 0, but there is a carry of 1 so it is 1 + 0 + 1. That's 0 with a 1 carried again:

```
  1
0 1 0 1 1₂
0 1 1 1 0₂
-----------
    0 0 1₂
```

Now the column is 1 + 1 with a 1 carried, or 1 + 1 + 1. This is 1 with a carry of 1:

```
1
0 1 0 1 1₂
0 1 1 1 0₂
----------
  1 0 0 1₂
```

Finally, the leading digits are 0+0 with a carry of 1, or 0 + 0 + 1. The answer is 11001_2. Is this correct? Well, 01011_2 is 11_{10} and 01110_2 is 14_2, and $11_{10} + 14_{10}=25_{10}$. The answer 11001_2 is, in fact, 25_{10}.

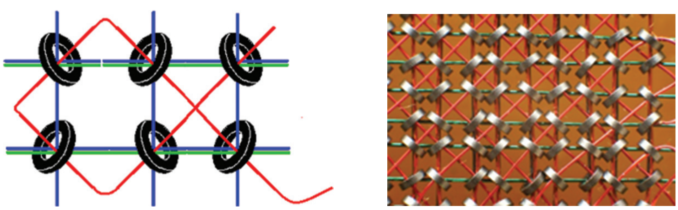
Binary numbers can be subjected to the same operations as any other form of number (i.e., multiplication, subtraction, division). In addition, these operations can be performed by electronic circuits operating on voltages that represent the digits 1 and 0.

0.2.2 Memory

Adding memory to computers was another important advancement. A computer memory must hold steady a collection of voltages that represent digits, and the digits are collected into sets, each of which is a number. A switch can hold a binary digit, but switches are activated by people. Computer memory must store and recall (retrieve) numbers when they are required by a calculation without human intervention.

The first memories were rather odd things: *acoustic delay lines* stored numbers as a sound passing through mercury in a tube. The speed of sound allows a small number of digits, around 500, to be stored in transit from a speaker on one end to a receiver on the other. A phosphor screen can be built that is activated by an electric pulse and draws a bright spot on a screen that needs no power to maintain it. Numbers can be saved as bright and dark spots (1 and 0) and retrieved using light sensitive devices.

Other devices were used in the early years, such as relays and vacuum tubes, but in 1947 the magnetic core memory was patented, in which bits were stored as magnetic fields in small donut-shaped elements. This kind of memory was faster and more reliable than anything used before, and even held the data in memory without power being applied, a handy thing in a power failure. It was also expensive, of course.



(a) (b)

Figure 0.8
(a) A diagram of core memory showing six bits.
(b) Actual core memory magnified to show the individual bits.

This kind of memory is almost never used anymore, but its legacy remains in the terminology: memory is still frequently referred to as *core*, and a *core dump* is still what many people call a listing of the contents of a computer memory.

Current computers use transistors to store bits and solid state memories that can hold billions of bits (*Gigabits*), but the way they are used in the computer is still the same as it was. Bits are collected into groups of 8 (a *byte*) and then groups of multiple bytes to for a *word*. Words are collected into a linear sequence, each numbered starting at 0. These numbers are called *addresses*, and each word, and sometimes each byte, can be accessed by specifying the address of the data that is wanted. Acquiring the data element at a particular location is called a *fetch*, and placing a number into a particular location is a *store*. A computer program to add two numbers might be specified as follows:

- Fetch the number at location 21.
- Fetch the number at location 433.
- Add those two numbers.
- Store the result in location 22.

This may seem like a verbose way to add two numbers, but remember that this can be accomplished in a tiny fraction of a second.

Memory is often presented to beginning programmers as a collection of mailboxes. The address is a number identifying the mailbox, which also contains a number. There is some special memory in the computer that has no specific address, and is referred to in various ways. When a fetch is performed there is a question concerning where the value that was fetched goes. It can go to another memory location, which is a *move* operation, or it can go into one of these special locations, called *registers*.

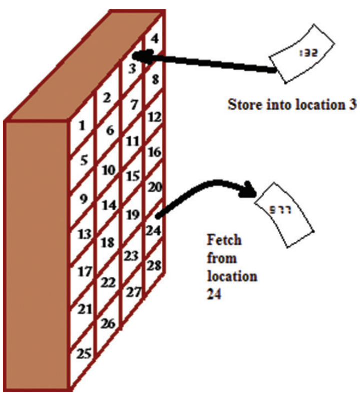


Figure 0.9
Memory as a set of cubbyholes or mailboxes, each with a unique address.

A computer can have many registers or very few, but they are very fast memory units that are used to keep intermediate results of computations. The simple program above would normally have to be modified to give registers that are involved in the operations:

- Fetch the number at location 21 into register R0.
- Fetch the number at location 433 into register R1.
- Add R1 and R0 and put the result into R3.
- Store R3 (the result) in location 22.

This is still verbose, but more correct.

0.2.3 Stored Programs

The final critical step in creating the modern computer occurred in 1936 with Alan Turing's theoretical paper on the subject, but an actual computer to employ the concept was not built until 1948 when the Manchester Small-Scale Experimental Machine ran what is considered to be the first stored program. It has been the basic method by which computers operate ever since.

The idea is to store a computer program in memory locations instead of on cards or in some other way. Programs and data now co-exist in memory, and this also means that computer programs have to be encoded as numbers; *everything* in a computer is a number. There are many different ways to do this, and many possible different instruction sets that have been implemented and various different configurations of registers, memory, and instructions. The computer hardware always does the same basic thing: first, it fetches the next instruction to be executed, and then it decodes it and executes it. Executing an instruction could involve more accesses to memory or registers.

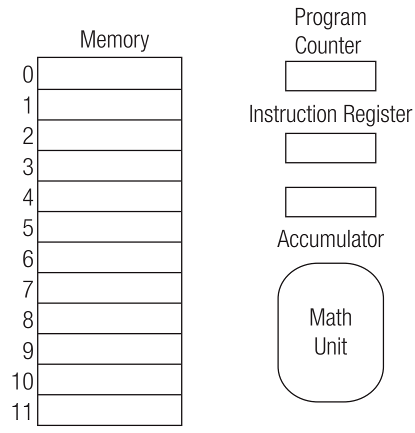


Figure 0.10
A simple fictional computer used to explain stored programs

This repeated fetch then executes a process called the *fetch-execute cycle*, which is at the heart of all computers. The location or address of the next instruction resides in a register called the *program counter*, and this register is incremented every time an instruction is executed, meaning that instructions will be placed in consecutive memory locations and will be fetched and executed naturally in that order. Sometimes the instruction is fetched into a special register too, called the *instruction register*, so that it can be examined quickly for important components like data values or addresses. Finally, a computer will need at least one register to store data; this is called the *accumulator*.

The stored program concept is difficult to understand. Imagine a computer that has 12-bit words as memory locations and that possesses the registers described above. This is a fictional machine, but it has some of the properties of an old computer from the 1960s called the PDP/8.

To demonstrate the execution of a program on a stored program computer, let's use a very simple program: add 21 and 433, and place the answer in location 11. As an initial assumption, assume that the value 21 is in location 9 and 433 is in location 10. The program itself resides in consecutive memory locations beginning at address 0.

Note that this example is very much like the previous two examples, but in this case, there is only one register to put data into, the accumulator. The program could perhaps look like this:

- Fetch the contents of memory location 9 into the accumulator.
- Add the contents of memory location 10 to the accumulator.
- Store the contents of the accumulator into memory location 11.

The program is now complete, and the result 21 + 433 is in location 11. Computer programs are normally expressed in terms that the computer can immediately use, normally as terse and precise commands. The next stage in the development of this program is to use a symbolic form of the actual instructions that the computer will use.

The first step is to move the contents of location 9 to the accumulator. The instruction that does this kind of thing is called *Load Accumulator*, shorted as the mnemonic LDA. The instruction is in location 0:

```
0: LDA 9   # Load accumulator with location 9
```

The text following the "#" character is ignored by the computer, and is really a comment to remind the programmer what is happening. The next instruction is to add the contents of location 10 to the accumulator; the instruction is ADD and it is placed in address 1:

```
1: ADD 10  # Add contents of address 10 to the accumulator
```

The result in the accumulator register is saved into the memory location at address 11. This is a Store instruction:

```
2: STO 11  # Answer into location 11
```

The program is complete. There is a Halt instruction:

```
3: HLT   # End of program</NL>
```

If this program starts executing at address 0, and if the correct data is in the correct locations, then the result 454 should be in location 11. But these instructions are not yet in a form the computer can use. They are characters, text that a human can read. In a stored program computer, these instructions must be encoded as numbers, and those numbers must agree with the ones the computer was built to implement.

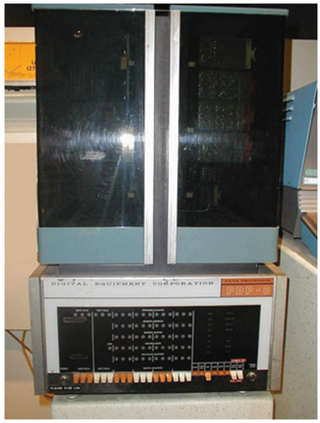


Figure 0.11
An actual PDP-8 computer. Programs were entered as binary numbers using the switches on the front console. This was the smallest computer of its time.

An instruction must be a binary number, so all of the possible instructions have numeric codes. An instruction can also contain a memory address; the LDA instruction specifies a memory location from which to load the accumulator. Both the instruction code and the address have to be placed into one computer word. The designers of the computer decide how that is done.

This computer has 12-bit words. Imagine that the upper 3 bits indicate what the instruction is. That is, a typical instruction is formatted as shown in Figure 0.12.

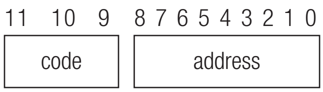


Figure 0.12
The format of a binary instruction.

There are 9 bits at the lower (right) end of the instruction for an address, and 3 at the top end for the code that represents the instruction. The code for LDA is 3; the code for ADD is 5, and the code for STO is 6. The HLT on most computers is code 0. Here is what the program looks like as numbers:

```
Code 3   Address 9
Code 5   Address 10
Code 6   Address 11
Code 0   Address 0
```

These have to be made into binary numbers to be stored in memory. For the LDA instruction, the code 3_{10} is 011_2 and the address is $9_{10} = 000001001_2$, so the instruction as a binary number is 011 000001001_2, where the space between the code and the address is only present to make it obvious to a person reading it.

The ADD instruction has code 5_{10}, which is 101_2, and the address is 10, which in binary is 0001010_2. The instruction is 101 000001010_2.

The STO instruction has code 6, which is 110_2 and the address is 11, which is 001011_2. The instruction is 110 000001011_2.

The HLT instruction is code 0, or in 12-bit binary, 000 000000000_2.

The codes are made up by the designers of the computer. Figure 0.13 shows an example of when memory is set up to contain this program.

	Memory
0	011000001001
1	101000001010
2	110000001011
3	000000000000
4	000000000000
5	000000000000
6	000000000000
7	000000000000
8	000000000000
9	000000010101
10	000110110001
11	000000000000

Figure 0.13
The simple example program as it looks in memory.

This is how memory looks when the program begins. The act of setting up the memory like this so that the program can execute is called *loading*. The binary numbers in memory locations 9 and 10 are 21 and 433, respectively, which are the numbers to be summed.

Of course, there are more instructions than these in a useful computer. There is not always a subtract instruction, but subtraction can be done by making a number negative and then adding, so there is often a NEGate instruction. Setting the accumulator to zero is a common thing to do so there is a CLA (Clear Accumulator) instruction; and there are many more.

The fetch-execute cycle involves fetching the memory location addressed by the program counter into the instruction register, incrementing the program counter, and then executing the instruction. Execution involves figuring out what instruction is represented by the code and then sending the address or data through the correct electronic circuits.

A very important instruction that this program does not use is a *branch*. The instruction BRA 0 causes the next instruction to be executed starting at memory location 0. This allows a program to skip over some instructions or to repeat some many times. A conditional branch changes the current instruction if a certain condition is true. An example would be "Branch if Accumulator is Zero (BAZ)." which is only performed if, as the instruction indicates, there is a value of zero in the accumulator. The combination of arithmetic and control instructions makes it possible for a programmer to describe a calculation to be performed very precisely.

0.3 COMPUTER SYSTEMS ARE BUILT IN LAYERS

Entering a program as binary numbers using switches is a very tedious, time-consuming process. Lacking a disk drive, the early computers depended on other kinds of storage: punch cards or paper tape. It should be understood that because there was no permanent storage, booting one of these machines often meant toggling a small "boot loader" program, then reading a paper tape. Now the computer would respond sensibly to its peripheral devices, like a printer or card reader. The paper tape contained a primitive 'operating system' that would control the few devices available. That's what operating systems do: allocate resources and control devices.

The boot loader (bootstrap program) is the lowest layer of software. It was provided by the computer manufacturer but had to be entered by the user. The paper tape system was the second layer, and the user did not have to write this program. Gradually, more and more layers were written to provide the user with a high level of abstraction rather than having to understand the entire machine.

When disk drives became available, the operating system was stored on them, and a bootstrap loader was saved in a special section of memory that could not be erased (read only memory) so that when the computer was turned on, it would run the loader, which would load the operating system. This is essentially what happens today on Windows.

This operating system on the disk drive is a third layer of software. It provides basic hardware allocation functionality and also gives the user access to some programs to use for printing and saving things on disk – a *file system*.

0.3.1 Assemblers and Compilers

Programming a computer could still be a daunting task if done in binary, so the first thing that was provided was an *assembler*. This was a program that permitted a programmer to enter a text program that could be converted into a binary executable. It allowed memory locations to be named instead of using an absolute number as an address, and would convert text operation codes and addresses into a binary program. The addition program from the previous section could be written in assembler as follows:

```
         LDA Data1
         ADD Data2
         STO Res
         HLT
Data1:   21
Data2:   433:
Res:     0
```

Usually, one line of text in an assembler corresponds to a single instruction or memory location. It's the same program, but is easier for a programmer to understand because of the named memory locations and mnemonic instruction names.

It is much harder to describe *how* a compiler works, but relatively easy to explain *what* it does. A compiler translates high level language statements into assembler, which in turn converts it into binary code. Compilers translate statements like

```
A = 21
B = 433
C = A+B
```

into executable code. It is a very complex process, but essentially it allows the programmer to declare that certain names represent integers, that values are to be assigned, and that arithmetic can be done. There are also more complex statements, like the conditional execution of code and function calls with parameters, as will be seen in later chapters.

Compilers also implement input and output from the user (reading from a keyboard and writing to the video screen), sophisticated data types, and mathematical functions. An *interpreter*, which is what the language Python is, does a part of the compilation process but does not produce executable code. Instead it simulates the execution of the code, doing most of the work in software. The Java language does a similar thing in many cases.

The programs that someone writes (software) creates another layer for someone to use. An example might be a database management system that gives a user access to a computer that can query data for certain kinds of values. A graphics system gives a programmer access to a set of operations that can draw pictures.

0.3.2 Graphical User Interfaces (GUIs)

Most users now interface with their computers through a keyboard, one of the first devices to be interfaced to a computer, a mouse, the first device to permit 2D navigation on a screen, and Windows, a graphical construction that allows many independent connections to a computer to share a single video screen. GUIs are popular because they improve the user's perception of what is happening on a computer. Previous computer interfaces were completely text based, so if there was a problem that the user could not see, it would go unnoticed.

GUIs, however, are difficult to program. Just opening a new window in a Microsoft-based operating system can require scores of lines of C++ code that would take a great deal of time to understand. Naturally, it is the job of a programmer to be able to do this, but it means that the average user could not create their own software that manipulated the interface in any reasonable way. So, what is a window and what's involved in a GUI?

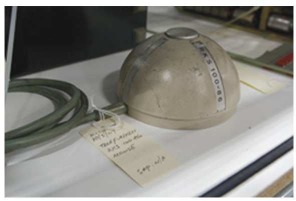


Figure 0.14
The first computer mouse. *https://commons.wikimedia.org/wiki/File:Telefunken_Rollkugel_RKS_100-86.jpg*

Figure 0.15
Englebart's computer mouse.

A window, in the operating system sense, is a rectangle on the computer screen within which an exchange of information takes place between the user and the system. The rectangle can generally be resized, removed from the screen temporarily (minimized), moved, and closed. It can be thought of as a virtual computer terminal in that each one can do what the entire video screen was needed to do in early systems. When the window is active, a user can type information to be received by the program controlling it, and can manipulate graphical objects within the window using a mouse, or more recently by using their fingers on a touch screen.

The mouse is a variation on the tracker ball, the German engineering company *Telefunken* devised a working version and was the first to sell it. A mouse is linked through software to a cursor on the screen, and left-right motions of the mouse cause left-right motions of the cursor; forward and backward motions of the mouse cause the cursor to move up and down the screen. When the cursor is inside of a window then that window is active. A mouse has buttons, and pressing a mouse button activates whatever software object is related to the cursor position on the screen.

Widgets

A widget is a graphical object drawn in a window or otherwise on a computer screen that can be selected and/or operated using the mouse and mouse buttons. It is connected to a software element that is sent a control signal or numerical parameter by virtue of the widget being manipulated. A widget is exemplified by the *button*, a very commonly used widget on Web pages and interfaces. Buttons can be used to display information as well as to control a program. Some popular widgets are as follows:

Figure 0.16
A button.

Figure 0.17
A radio button.

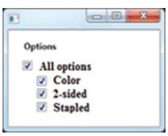


Figure 0.18
A check box.

Button: When the mouse cursor is within the boundaries of the button on the screen, the button is said to be activated. Pressing a mouse button when the button widget is activated causes the software connected to the button to perform its function.

Radio Button: A set of two or more buttons used to select from a set of discrete options. Only one of the buttons can be selected at a time, meaning that the options are mutually exclusive.

Check Box: A way to select a set of options from a larger set. This widget consists of a collection of boxes or buttons that can be chosen by clicking on them. When chosen, they indicate that fact by using a graphical change, sometimes a check mark but sometimes a color or other visual effect.

Slider: A horizontal or vertical control with a selection tool that can be slide along the control. The relative position of the control dictates the value that the widget provides. This value is often displayed in a text box, and the range is also commonly displayed.

Figure 0.19
Slider.

Drop-down List: A box containing text that displays a complete set of options that can be displayed when the mouse button is clicked within it. Then any one of the options can be selected using the mouse and the mouse button.

Icon: An icon is a small graphical representation (pictogram) that represents the function of a program or file. When selected the program will execute or the file will be opened.

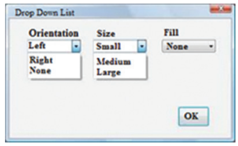


Figure 0.20
Drop-down list.

Figure 0.21
Icon.

There are many other widgets and variations on the ones shown here. There are two basic principles at play:

1. The widget represents an activity using a commonly understood symbol, and performs that activity, or one related to the symbol, when selected using the mouse. This is a graphical and tactile operation that replaces the typing of a command in previous computer systems.
2. The software that implements the widget is a *module*, software that can be reused and reconfigured for various circumstances. A button can be quickly created to perform any number of tasks because the program that implements it is designed for that degree of flexibility.

0.4 COMPUTER NETWORKS

Schools, offices, and some homes are equipped with computer *networks*, which are wires that connect computers together and software and special hardware that allows the computers to communicate with each other. This allows people to send information to each other through their computers. But how does this really work?

Computers use electricity to perform calculations on binary numbers. Arbitrary voltages represent 0 and 1, and those voltages are sent along a wire no matter how long it is and still be numbers at the receiving end. As long as two computers are connected, this works well, but if two wires are needed to connect any two computers, then six wires are needed to fully connect three computers to each other and twelve to connect four computers. A room with thirty networked computers would be full of wires (870 to each computer)!

Hawaii has an unusual problem when it comes to computer network communication. It is a collection of islands. Linking them by cables is an expensive proposition. In the early 1970s, the technicians at the University of Hawaii decided to link the computers using radio. Radio transmission is similar to wire transmission in many practical ways, and allocating 35 radio frequencies to connect one computer on each island to all of the others would have been possible, but their idea was better. They used a single radio link for all computers. When a computer wanted to send information along the network, it would listen to see if another computer was already doing so. If so, it would wait. If not, it would begin to send data to *all* of the other computers and would include in the transmission a code for which computer was supposed to receive it. All could hear it, but all would know which computer was the correct destination so the others would ignore it. This system was called *Alohanet*.

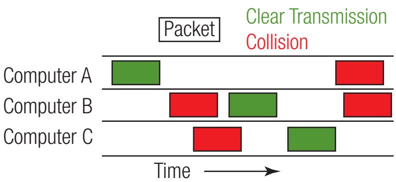


Figure 0.22
Packets transmitted on a network. Red ones are collisions.

There is a problem with this scheme. Two or more computers could try to send at almost the same time, having noted that no other computer was sending when they checked. This is called a *collision*, and is relatively easy to detect; the data received is nonsense. When that happens, each computer waits for a random time, checks again, and tries again to send the data. An analogy would be a meeting where many people are trying speak at once.

Obviously, the busier the network is, the more likely a collision will be, and the re-transmissions will make things worse. Still, this scheme works very well and is functioning today in the form of the most common networking system in earth – *Ethernet*.

Ethernet is essentially Alohanet along a wire. Each computer has one connection to it, rather than connections to each of the possible destinations, and collisions are possible. There is another consideration that makes this scheme work better, and that it is use of *packets*. Information along these networks is sent in fixed-size packages of a few thousand bytes. In this way, the time needed to send a packet should be more or less constant, and it's more efficient than sending a bit or a byte at a time.

Each packet contains a set of data bytes intended for another computer, so within that packet should be some information about the destination, the sender, and other important data. For instance, if a data file is bigger than a packet, then it is split up into parts to be sent. Thus, a part of the packet is a sequence number indicating which packet it is (e.g., number 3 of 5). If a particular packet never gets received, then the missing one is known, and the receiver can ask the sender for that packet to be resent. There are also codes to determine whether an error has occurred.

0.4.1 Internet

The Internet is a computer network designed to communicate reliably over long distances. It was originally created to be a reliable communications system that could survive a nuclear attack, and was funded by the military. It is *distributed*, in that data can be sent from one computer to another in a chain until it reaches its destination.

Imagine a collection of a few dozen computers, and that each one is connected to multiple others, but not directly to all others. Computer A wishes to send a message to computer B, and does so using a packet that includes the destination. Computer A sends the message to all computers that it is connected to. Each of those computers sends it to all of the computers that they are connected to, and so on until the destination is reached. All of the computers will receive every message, which is inefficient, but so long as there exists some path from A to B, the message will be delivered.

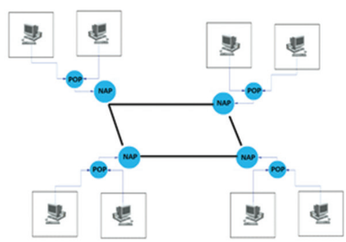


Figure 0.23
The organization of the Internet.

It would be hard to tell when to stop sending a message in this scheme. Another way to do it is to have a table in each computer saying which computers in the network are connected to which others. A message can be sent to a computer known to be a short path to the destination, one computer at a time, and in this case not all computers see the message, only the ones along the route do. A new computer added to the network must send a special message to all of the others telling them which of the existing computers it is directly connected to, and this message will propagate to all machines, allowing them to update their map. This is essentially the scheme used today.

The Internet has a hierarchy of communication links and processors. First, all computers on the Internet have a unique IP (*Internet Protocol*) address through which they are reached. Because there are many computers in the world, an IP address is a large number. An example is 172.16.254.1 (obtained from Wikipedia). When a computer in, say, Portland want to send a message to, for example, London, the Portland computer composes a packet that contains the message, its address, and the recipient's address in London. This message is sent along the connection to its Internet service provider, which is a local computer, at a relatively low speed, perhaps 10 megabits per second. The service provider operates a collection of computers designed to handle network traffic. This is called a *Point of Presence* (POP), and it collects messages from a local area and concentrates them for transmission further down the line.

Multiple POP sites connect to a Network Access Point (NAP) using much faster connections than users have to connect with the POP. The NAP concentrates even more users, and provides a layer of addressing that can be used to send the data to the destination. The NAP for the Portland user delivers the message to a relatively local NAP, which sends it to the next NAP along a path to the destination in London using an exceptionally fast (high bandwidth) data connection. The London NAP sends the message to the appropriate local POP, which in turn sends it to the correct user.

An important consideration is that the message can be read by any POP nor NAP server along the route. Data sent along the Internet is public unless it is properly encrypted by the users.

0.4.2 World Wide Web

The World Wide Web, or simply the *Web*, is a layer of software above the Internet protocols. It is a way to access files and data remotely through a visual interface provided by a program that runs on the user's computer, a *browser*. When someone accesses a Web page, a file that describes that page is downloaded to the user's browser and displayed. That file is text in a particular format, and the file name usually ends in .html or .htm. The file holds a description of how to display the page: what text to display, where images can be found that are part of the page, how the page is formatted, and where other connected pages (links) are found on the Internet. Once the file is downloaded, the local (receiving) computer performs the work concerned with the display of the file, such as playing sounds and videos, and drawing graphics and text.

The Web is the basis for most of the modern advances in social networking and public data access. The Internet provides the underlying network communications facility, while the Web uses that to fetch and display information requested by the user in a visual and auditory fashion. Podcasts, blogs, and wikis are simple extensions of the basic functionality.

The Web demands the ability for a user in Portland to request a file from a user in London and to have that file delivered and made into a graphical display, all with a single click of a mouse button. Web pages are files that reside on a computer that has an IP address, but the IP address is often hidden by a symbolic name called the Universal Resource Locator (URL). Almost everyone has seen one of these (*http://www.facebook.com* is one example). Web pages have a unique path or address based on a URL. Anyone can create a new web page that uses its very own unambiguous URL at any time, and most of the world would be able to view it.

The Web is an example of what programmers call a *client-server* system. The client is where the person requesting the Web page lives, and is making a request. The server is where the Web page itself exists, and it satisfies the request. Other examples of such systems would be online computer games, Email, *Skype*, and *Second Life*.

0.5 REPRESENTATION

When applying a computer to a task or writing a program to deal with a type of data that seems to be non-numeric, the issue of how to represent the data on the computer invariably arises. Everything stored and manipulated on a computer has to be a number. What if the data is not numeric?

A fundamental example of this is character data. When a user types at the computer keyboard, what actually happens? Each key, and some key combinations (e.g., the shift key and "1" held down at the same time), when pressed result in electrical signals being sent along a set of wires that connect to an input device on the computer, a USB port perhaps. Pressing a key results in an identifiable combination of wires being given a voltage. This is, in fact, a representation of the character, and one that underlies the one that will be used on the computer itself. As described previously, voltages can be used to represent binary numbers.

The representation of characters on a computer amounts to an assignment of a number to each possible character. This assignment could be arbitrary, and for some data it is. The value of the letter "a" could be 1, "b" could be 12, and "c" could be 6. This would work, but it would be a poor representation because characters are not in an arbitrary order. The letter "b" should be between "a" and "c" in value because it is positioned there in the data set, the set of characters. In any case, when creating a numeric representation the first rule is as follows:

1. If there are a relatively small number of individual data items, assign them consecutive values starting at 0. If there is a practical reason to start at some other number, then do so.

   The second rule considers the existing ordering of the elements:

2. In cases where data items are assigned consecutive values, assign them in a manner that maintains any pre-defined *order* of the elements.

   This means that in a definition of characters the letter 'a', 'b', and 'c' should appear in that order.

3. In cases where data items are assigned consecutive values, assign them in a manner that maintains any pre-existing *distance* between the elements.

   This means that the letters "a," "b," and "c" would be adjacent to each other in the numeric representation because they are next to each other in the alphabet. The character classes also have consecutive codes so that the code for "0" is adjacent to, and smaller than, the code for "1," and so on. This set of three rules creates a reliable mapping of characters to numbers. However, there are more rules for making representations.

4. In cases where the data items are assigned consecutive values, assign them in a manner that simplifies the operations that are likely to be performed on the data.

   In the present example of character data, there are relatively few places where this rule can be invoked, but one would be when comparing characters to each other. A character "A" is usually thought to come before “a,” so this means that all of the uppercase letters come before all lowercase ones, in a numerical sense. Similarly, “0” comes before “A,” so all digits come before all letters in the representation. A space would come before (i.e., have a smaller value) than any character that prints.

One of the most common character representations, named the *American Standard Code for Information Interchange* or *ASCII* has all of these properties, and a few others. The standard ASCII character set lists 128 characters with numerical codes from 0 to 127. In the table below, each character is listed with the code that represents it. They appear in numerical order. The characters in orange are telecommunications characters that are never used by a typical computer user; green characters are non-printing characters that are used for formatting text on a page; letters and numbers for English are red; special characters, like punctuation, are blue. The space character is in some sense unique, and it is black.

Table 0.01

American Standard Code for Information Interchange

Code	Char	Code	Char	Code	Char	Code	Char	Code	Char	Code	Char	Code	Char	Code	Char
0	NUL	16	DLE	32	Space	48	0	64	@	80	P	96	‘	112	p
1	SOH	17	DC1	33	!	49	1	65	A	81	Q	97	A	113	q
2	STX	18	DC2	34	“	50	2	66	B	82	R	98	B	114	r
3	ETX	19	DC3	35	#	51	3	67	C	83	S	99	C	115	s
4	EOT	20	DC4	36	$	52	4	68	D	84	T	100	D	116	t
5	ENQ	21	NAK	37	%	53	5	69	E	85	U	101	E	117	u
6	ACK	22	SYN	38	&	54	6	70	F	86	V	102	F	118	v
7	BEL	23	ETB	39	‘	55	7	71	G	87	W	103	G	119	w
8	BS	24	CAN	40	(	56	8	72	H	88	X	104	H	120	x
9	TAB	25	EM	41	)	57	9	73	I	89	Y	105	I	121	y
10	LF	26	SUB	42	*	58	:	74	J	90	Z	106	J	122	z
11	VT	27	ESC	43	+	59	;	75	K	91	[	107	K	123	{
12	FF	28	FS	44	,	60	<	76	L	92	\	108	L	124	|
13	CR	29	GS	45	-	61	=	77	M	93	]	109	M	125	}
14	SO	30	RS	46	.	63	>	78	N	94	^	110	N	126	~
15	SI	31	US	47	/	63	?	79	O	95	_	111	O	127	DEL

If there is a very large number of possible data values, then enumerating them would be unreasonable. There are other ways to solve that sort of problem.

5. Try to break the data into enumerable parts.

   Dates can be an example of this kind of data. There are too many dates to store as discrete values, as there is no actual day 0, and there is no practical final day in the general case. However, a common way to state a date is to give a year, a month, and a day. This is awkward from a computer's perspective because of the variable number of days in each month, but it works well for humans. Each component is enumerable, so a possible representation for a date would be as three numbers: year, month, day. It would be YYYYMMDD, where YYYY is a four-digit year, MM is a number between 0 (January) and 11 (December), and DD is a number between 0 and 30, which is the day of the month.

   This representation should keep the dates in the correct sequence, so December 9, 1957, (19571108) comes after Aug 24, 1955 (19550723). However, another common operation on dates is to find the number of days between two specified dates. This is difficult, and the only representation that would simplify it would be to start counting days at a zero point. If that zero point is Jan 1, 1900 then the representation for the date October 31, 2017 is 43037. The number of days between two dates is then found by subtraction. However, printing the date in a form for humans to read is difficult. When selecting a representation, the most common operations on the data should be the easiest ones to perform.

   Another example of this sort or representation is *color*, which will be discussed in detail in a later chapter.

6. When the data is part of a continuous stream of real values, then it may be possible to *sample* them and/or *quantize* them.

Sampling means to represent a sequence by using a subset of the values. Imagine a set of numbers coming from a seismometer. The number sequence represents measurements of the motion of the ground captured continuously by a mechanical device. It is normally acceptable to ignore some of these values, knowing that between a value of 5.1 (whatever that means) and a value of 6.3, the numbers would have taken on all possible values between those two; that's what continuous means.

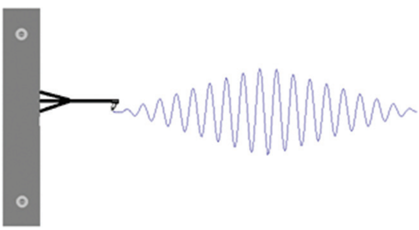


Figure 0.24
A continuous set of data has a measurable value between any other two.

Instead of capturing an infinite number of values, which is not possible, why not capture a value every second, or tenth of a second, or at whatever interval makes sense for the data concerned? Some data will be lost. The important thing is not to lose anything valuable.

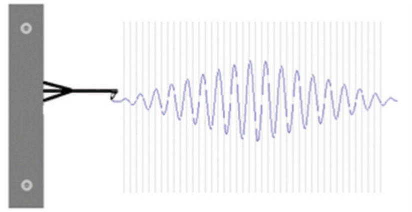


Figure 0.25
Sampling means picking an interval and only keeping the data values at those locations. The vertical lines here are sampling positions.

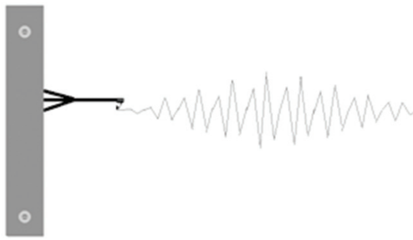


Figure 0.26
The resulting signal is not as smooth as the original (lower resolution).

The same thing can be done spatially. If someone is building a road, then it must be surveyed. A set of height values for points along the area to be occupied by the road is collected so that a model of the 3D region can be built. But between any two points that can be sampled there is another point that could be sampled, on to infinity. Again, a decision is made to limit the number of samples so that the measurements are made every few yards. This limits the accuracy, but not in a practical way. The height at some specific point may not have been measured, but it can be estimated from the numbers around it.

The distance between two sample points is referred to as the *resolution*. In spatial sampling, it is expressed in distance units, and says something about the smallest thing that can be precisely known. In time sampling, it is expressed in seconds.

Quantization means how accurately each measurement is known. In high school science, numbers that are measurements are given to some number of significant figures. Measuring a weight as 110.9881 pounds would seem impossibly accurate, and 111 would be a more reasonable number. Quantization in computer terms would be *restricting the number of bits used to represent the value*. Something that is stored as an 8-bit number can have 256 distinct values, for example. If the world's tallest person is under 8 feet tall, then using 8 bits to represent height would mean that 8 feet would be broken up into 256 parts, which is 0.375 inches; that is 8 feet × 12 inches/foot = 96 inches, and dividing this into 256 parts = 0.375. The smallest difference in height that could be expressed would be this value, a little over a third of an inch.

Quantization is reflected in the representation as a possible error in each value. The greater the number of bits per sample, the more accurately each one is represented. The use of sampling and quantization is very common, and is used when saving sounds (MP3), images (JPEG), and videos (AVI).

There are other possible options for creating a representation for data, but the six basic ideas here will work most of the time, alone or in combination. A programmer must understand that she or he will need to wisely choose the representations for the data. A poor choice will result in more complex code, which generates more errors and less overall satisfaction with the result. Spending a little extra time at the beginning analyzing the possibilities can save a lot of effort later.

0.6 SUMMARY

Computers are devices that humans built to facilitate complex calculations and are tools for rapidly and accurately manipulating numbers. When humans communicate with each other, we use a language. Similarly, humans use languages to communicate with computers. A computer program can be thought of as a sequence of operations that a computer can perform to accomplish a calculation. The program must be expressed in terms that the computer can do.

Early computers were mechanical, using gears to represent numbers. Electronic computers usually use two electrical states or voltages to represent numbers, and those numbers are in binary or base-2 form. Electronic computers have memories that can store numbers, and everything stored in memory must be in numeric form. That includes the instructions that the computer can execute.

Computers have been around long enough to provide many layers of computer programs that can assist in their effective use: graphical user interfaces, assemblers, compilers for programming languages, Web browsers, and accounting packages provide a user with a different view of a computer and a different way to use it. Computers can exchange data between each other using wires over short distances (computer network) and long ones (Internet). The World Wide Web sits atop the Internet and provides an easy and effective way for computers all over the world to exchange information in any form.

Everything stored and manipulated on a computer has to be a number. What if the data is not numeric? In that case a numeric representation has to be devised that effectively characterizes the information while permitting its efficient manipulation.

Exercises

1. Convert the following binary numbers into decimal:
   a) `0100000`
   b) `0000100`
   c) `0000111`
   d) `0101010`
   e) `0110100101`
   f) `0111111`
   g) `110110110`
2. Convert the following decimal numbers into binary:
   a) `10`
   b) `100`
   c) `64`
   d) `128`
   e) `254`
   f) `5`
   g) `999`
3. Core memory would not erase itself when its power source was removed. Give reasons why this is a valuable property.

   ____

   ____

   ____

4. Specify a device that is used for:
   a) Output only
   b) Input only
   c) Both input and output
5. Ada, Countess of Lovelace, is generally considered to be the first programmer, but some contrary information has come to light recently. Search the literature for two articles on each side of the argument and formulate a conclusion.

6. What is the difference between a compiler and an interpreter? Give an example of each.

7. Identify a GUI widget that was not discussed in this chapter. Sketch its appearance and describe its operation. Give an example of a situation where it might be used.

8. Give the ASCII codes for the following characters:

a) `'P'`

b) `';'`

c) `'r'`

d) `','`

e) `'='`

9. What is the value of the ASCII code for the character "1" minus the code for the character "0"? What is 2-0? What does this say about converting from the character form of a number into its numeric value in general?

10. Consider the imaginary computer devised in this chapter. It has a memory in which each location has 12 binary digits (bits) to store a number. In one of the memory locations the value 101000000000 is seen. What is this? Is it an instruction, a number, a character, an address, or something else? How can this be determined?

Notes and Other Resources

http://www.vandermark.ch/pdp8/index.php?n=PDP8.Emulator

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3. James Essinger (2004). *Jacquard's web*. Oxford University Press, Oxford. ISBN 978-0-19-280578-2.

4. Tony Sale, *The Colossus Computer 1943–1996: How It Helped to Break the German Lorenz Cipher in WWII*, M.&M. Baldwin, Kidderminster, 2004; ISBN 0-947712-36-4.

5. Stephen Stephenson (2013), *Ancient Computers, Part I - Rediscovery*, Edition 2, ISBN 1-4909-6437-1.

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7. Michael R. Williams (1998). *The "Last Word " on Charles Babbage*. *IEEE Annals of the History of Computing 20* (4): 10–4. doi:10.1109/85.728225.

8. Javier Yanes (2015) *Ada Lovelace: Original and Visionary, but No Programmer*, OpenMind, 09 December 2015. https://www.bbvaopenmind.com/en/ada-lovelace-original-and-visionary-but-no-programmer/

CHAPTER 1

COMPUTERS AND PROGRAMMING

In this chapter

The vast majority of computers fthat most people encounter are *digital* computers. This refers to the fact that the computer works on numbers. Other kinds of computer do exist but are not as common. *Analog* computers operate in a number of other ways, but are usually electrical (they manipulate electrical voltages and currents). They may be mechanical and use gears and shafts to calculate a mechanical response.

The fact that any problem must be expressed in numerical form can be challenging. *I'm not good at math* is a common complaint, and the belief that computer programming requires a knowledge of advanced mathematics is used as a reason to not study programming. The kind of math commonly needed for programming would more properly be called arithmetic, not math.

In order for a problem to be solved using a computer, the problem must be expressed in a way that manipulates numbers and the data involved must be numeric. This is often accomplished by some kind of encoding of the data. It is so common that the process is invisible on modern computers. Most data have a variety of encodings that have been used for years and are taken for granted: images in JPEG format or sounds in MP3 are examples of commonly used encoding of data into numbers.

What can computers do with numbers? Addition, subtraction, multiplication, and division are the basic operations, but computers can compare the value of numbers, too.

1.1 SOLVING A PROBLEM USING A COMPUTER

The process of solving a problem using a computer begins with a detailed specification of the problem to be solved. Unless the problem is completely understood, its solution on a computer is impossible. Then we examine the problem to see what methods that we know about and what programs we already have could be used in its solution. At this stage we're diving the problem in to the part that we know how to solve right away, and the part that we do not. The latter part has to be examined in more detail until a solution can be proposed. Then we create an outline of the solution, often on paper using human language; this is *pseudocode*, and differs in style from person to person. This is translated into computer language and then typed into computer form using a keyboard. The resulting text file is called a *script*, *source code*, or more commonly just the *computer program*.

A program called a *compiler* takes this program and converts it into a form that can be executed on the computer. Basically, all programs are converted into a set of numbers called machine code which the computer can execute.

We are going to learn a language called *Python*. It was developed as a general-purpose programming language and is a good language for teaching because it makes a lot of things easy. Quite a few applications are built using Python, such as the games *Eve Online* and *Civilization IV*, *BitTorrent*, and *Dropbox*. It is a bit like a lot of other languages in use these days in terms of structure (syntax) but has some simplifying ideas that will be discussed in later chapters.

In order to use a programming language there are some basic concepts and structures that need to be understood at a basic level. Some of these concepts are introduced in this chapter and the rest of the book teaches you to program by example; in all cases, coding examples are introduced by stating a problem to be solved. The problems to be solved in this chapter include a simple guess-a-number game and the game of rock-paper-scissors. These problems serve as the motivation for learning more about either the Python language itself or about methods of solving problems. Any computer programs in this book will execute on a computer running any major operating system once the free Python language download has been installed.

1.2 EXECUTING PYTHON

Installing Python is not too difficult, and involves downloading the installer, running it, and perhaps configuring a few specific details. This process can be found in Appendix I. Once installed, there are a few variations that can be used with it, the simplest probably being the *Python Graphical User Interface* or *GUI*. If you are running Python on a Windows PC, look at the Start menu for Python and click a link named "IDLE (Python GUI)," as shown in Figure 1.1. Click on this and the user interface will open. Click the mouse in the GUI window so that you can start typing characters there.

Python can be run interactively in the GUI window. The characters ">>>" are called a *prompt*, and indicate that Python is waiting for something to be typed at the keyboard. Anything typed here will be presumed to be a Python program, or at least part of one. As a demonstration, type "1" followed by pressing the Enter key. Python responds by printing "1." Why? When "1" was typed, it was a Python expression, something to be evaluated. The value of "1" is simply "1," so that was the answer Python computed.

Now type "1+1." Python responds with "2." Python inputs what the user/programmer types, evaluates it as a mathematical (in Python form) expression, and

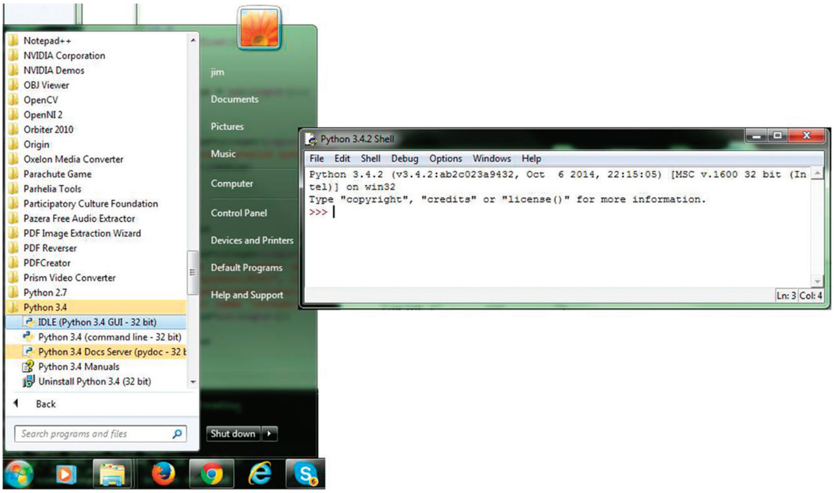


Figure 1.1
Running the Python GUI.

prints the answer. This is not really programming yet, because a basic two-dollar calculator can do this, but it is certainly a start.

IDLE is good for many things, but eventually a more sophisticated environment is needed, one that can indent automatically, detect some kinds of errors, and allow programs to be run and debugged and saved as *projects*. This kind of system is called an *integrated development environment*, or IDE. There are many of these available for Python, some that are expensive and some that are freely downloadable. The code in this book has been compiled and tested using *PyCharm*, but most IDEs are acceptable. It is largely a matter of personal preference. Basic PyCharm is free, but there is a more advanced version that costs a small amount of money.

An advantage of an IDE is that it is easy to type in a whole program, run it, find the errors, fix them, and run it again. This process is repeated until the program works as desired. Multiple parts of a large program can be saved as separate files and collected together by the IDE, and they can be worked on individually and tested together. A good IDE uses color to indicate syntax features that Python understands and can show some kinds of error while the code is being entered.

A program, just like any sentence or paragraph in English, consists of symbols, and order matters. Some symbols are special characters with a defined meaning. For example, "+" usually means *add*, and "-" usually means *subtract*. Some symbols are words. Words defined by the language, like *if*, *while*, and *true*, cannot also be also defined by a programmer – they mean what the language says they mean, and are called *reserved words*. Some names have a definition given by the system but can be reused by a programmer as needed. These are called *predefined names* or *system variables*. However, some words can be defined by the programmer, and are the names for things the programmer wants to use in the program: *variables* and *functions* are examples.

1.3 GUESS A NUMBER

Games that involve guessing are common, and are sometimes used to resolve minor conflicts, such as who gets the next piece of cake or who gets the first kick at a football. It's also sometimes a way to occupy time, and can simply be fun. How can we write a program to have the user guess a number that the program has chosen?

There are many variations on this simple game. In one version, the number is to be guessed precisely. One person (the *chooser*) selects a number, an integer, in a specified range. "Pick a number between one and ten" is a typical expression of this kind of problem. The other person, the guesser, must choose a number in that range. If the guesser selects the correct number, then the guesser wins. This is a boring game and is biased in favor of the chooser.

A more interesting variation is to start with one guess and have the chooser then say whether the target number is greater than or less than the guessed number. The guesser then guesses again, and the process continues until the number is guessed correctly. The roles of guesser and chooser can now switch and the game starts again. The best guesser is the one who uses the fewest guesses.

A third alternative is to have multiple guessers. All guessers make their selection and the one who has chosen a number nearest the correct number is the winner. This is the best game for solving disputes, because it involves one guess from each person. Ties are possible, in which case the game can be played again.

1.4 ROCK–PAPER–SCISSORS

This game is used to settle disputes and make random decisions. There are actually competitions where money is at stake. A televised contest in Las Vegas had a prize of $50,000.

In this game, each of two players selects one item from the list (rock, paper, or scissors) in secret, and then both display their choice simultaneously. If both players selected the same item, then they try again. Otherwise, rock beats scissors, scissors beat paper, and paper beats rock. This contest can be repeated for a "best out of N" competition.

Both of these games form the first problem set, and serve as the motivation for learning the elements of the Python language.

1.5 SOLVING THE *GUESS A NUMBER* PROBLEM

The simple version of the guessing program has two versions depending on who is guessing. The computer should pick the number and the human user should guess, because the other way around involves some complex programming. Here's what has to happen for this game to be successful:

1. The computer selects a number.
2. The computer asks the player to guess.
3. The player types a number on the keyboard and the computer reads it in.
4. The computer compares the input number against the one that it selected and if the two agree, then the player wins. Otherwise, the computer wins.

The Python features needed to do this include printing a message, reading in a number, having a place to store a number (a variable), having a way to select a number, and having a way to compare the two numbers and act differently depending on the result.

The second version requires the above, plus a way to repeat the process in cases when the guess is wrong and until it is correct. In this case the method becomes:

1. The computer selects a number.
2. The computer asks the player to guess.
3. The player types a number on the keyboard and the computer reads it in.

4. The computer compares the input number against the one that it selected and if the two agree, then the player has guessed correctly. Exit to Step 7.
5. The computer determines whether the guess is higher or lower than the actual number and prints an appropriate message.
6. Repeat from Step 2.
7. Game over.

The repetition mechanism is the only new aspect to this solution, but is an essential component of Python and every other programming language.

1.6 SOLVING THE *ROCK-PAPER-SCISSORS* PROBLEM

The solution to this problem has no new requirements, but re-enforces the language features of the previous solutions. One solution to this problem is as follows:

1. Select a random choice form the three items rock, paper, or scissors. Save this choice in a variable named **choice**.
2. Ask the player for their choice. Use an integer value, where 1 = rock, 2 = paper, and 3 = scissors.
3. Read the player's selection into a variable named **player**.
4. If **player** is equal to **choice**:
5. Print the message "Tie. We'll try again."
6. Repeat from Step 1
7. If **player** is equal to rock
8. If **choice** is equal to scissors go to Step 17
9. Else go to Step 18
10. If **player** is equal to paper
11. If **choice** is equal to scissors go to Step 17
12. Else go to step 18
13. If **player** is equal to scissors
14. If **choice** is equal to rock go to Step 17
15. Else go to Step 18
16. Print error message and terminate.

17. Print "Computer wins" and terminate
18. Print "You win" and terminate

For each player selection, one of the alternate items will beat it and one will lose to it. Each choice is checked and the win/lose decision is made based on the known outcomes.

The solutions to both problems require similar language elements: a way to store a value (a *variable*), a way to execute specific parts of the program depending on the value of a variable or expression (an *if* statement), a way to read a value from the keyboard, a way to print a message on the screen, and a way to execute code repeatedly (a *loop*).

1.6.1 Variables and Values–Experimenting with the Graphical User Interface

A *variable* is a name the programmer defines to represent a value, usually a number or a text string. It represents the place where the computer stores that value; it is a symbol in text form, representing a value. Everything that a computer does is ultimately done with numbers, so the location of any thing is a number that represents the place in computer memory where that thing is stored. It's like offices in building. Each office has a number (its address) and usually has a name, too (the occupant or business found there). Additionally, the office has contents, and those contents are often described by the name given. Figure 1.2 shows a collection of offices in a building. In this metaphor, the office number corresponds to the address and the name (variable name), being more human friendly, is how it is often referred to by a person (programmer). In all cases, though, it is the contents of the office (location) that are important. The number and name are ways to access it. So, someone might say "*Bring me the Python manual from the Server Room*" or "*Bring me the Python manual from 607*" and both would mean the same thing. The Python manual is the content of location 607. Now, someone could say "*Put this Python manual in the Digital Media Lab*", which would change the content of location 611. In actual Python, the act of retrieving a value from a location does not change the content of that location, but instead makes a copy, but the basic metaphor is sound.

Not all strings or characters can be variable names. A variable cannot begin with a digit, for example, or with most non-alphabetic characters like "&" or "!," although in some cases beginning with "_" is acceptable. A variable name can contain upper- or lowercase letters, digits, and "_". Uppercase and lowercase letters are not considered the same, so the variables **Hello** and **hello** are different.

Figure 1.2
Variables are names that represent addresses, like offices in a building. The name is used in programming to represent the value found inside. These door signs are from the author's workplace.

A variable can change values but, unlike a real office, a simple variable can hold only one value at a time. The name chosen does not have to be significant. Programs often have variables named **i** or **x**. However, it is a good idea to select names that represent the kind of value that the variable contains so as to communicate that meaning to another person. For example, the value 3.1415926 should be stored in a variable named **pi**, because that's the name everyone else gives to this value.

In the GUI, type **pi = 3.1415926**. Python responds with a prompt, and that it has no value to print. If you now type **pi,** the response is **3.1415926**; the variable named **pi** that was just created now has a value.

In the syntax of Python, the name **pi** is a variable, the number **3.1415926** is a constant, but is also an *expression*, and the symbol = means *assign to*. In the precise domain of computer language, **pi = 3.1415926** is an *assignment statement* and gives the variable named **pi** the specified value.

Continuing with this example, define a new variable named **radius** to be 10.0 using an assignment statement **radius = 10.0**. If you type **radius** and press the "Enter" key, Python responds with **10.0**. Finally, we know that the circumference of a circle is **2πr** in math terms, or *2 times pi times the radius* in English. Type **2*pi*radius** into the Python GUI, and it responds with **62.831852**, which is the correct answer. Now type **circumference = 2*pi*radius** and Python assigns the value of the computation to the variable **circumference**.

Python defines a variable when it is given a value for the first time. The type of the variable is defined at that moment too; that is, if a number is assigned to a name, then that name is expected to represent a number from then on. If a string is assigned to a name, then that name is expected to be a string from then on. Trying to use a variable before it has been given a value and a type is an error. Attempting the calculation

area = side*side

is not allowed unless there is a variable named **side** already defined at this point. The following is acceptable because it defines **side** first, and then in turn is used to define **area**:

side = 12.0
area = side*side

The two lines above are called *statements* in a programming language, and in Python, a statement usually ends at the end of the line (the "Enter" key was pressed). This is a bit unusual in a computer language, and people who already know Java or C++ have some difficulty with this idea at first. In other computer languages, statements are separated by semicolons, not by the end of the line. In fact, in most languages the indenting of lines in the program does not have any meaning except to the programmer. In Python, that's not the case either, as will be seen shortly.

The expressions we use in assignments can be pretty complicated, but are really only things that we learned in high school (add, subtract, multiply, and divide). Multiplication and division are performed before addition and subtraction, which is called a *precedence rule*, so 3*2+1 is 7, not 9; otherwise *evaluation is done left to right*, so 6/3*2 is 4 (do the division first) as opposed to 1 (if the multiplication was done first). These are rules that should be familiar because it is how people are taught to do arithmetic. The symbol ****** means exponent *or to the power of*, so **2**3** is 2^3 which is 8, and this operator has a higher precedence (i.e., is done before) than the others. Parentheses can be used to specify the order of things. So, for example, **(2+3)**2** is 25, because the expression within the parentheses is done first, then the exponent.

1.6.2 Exchanging Information with the Computer

When using most programming languages, it is necessary to carefully design the communication with the computer program. This goes two ways: the program informs the user of information, such as the circumference of a circle given a specific radius, and the user may want to tell the program certain things, like the value of the radius with which to computer the circumference. We communicate with a program using *text*, characters typed into a keyboard. When a computer is presenting results, that text is often in the form of human language. "The circumference is 62.831852" could be such a message. The sentence is actually composed by a programmer and has a number or collection of numbers embedded within it.

Python allows a programmer to send a message to the screen, and hence to the user, using a **print** directive. This is the word **print** followed by a character string, which is often a set of characters in quotes. An example is as follows:

```
print ("The answer is yes.")
```

The parentheses are used to enclose everything that is to be printed; such a statement can print many strings if they are separated by commas. Numbers will be converted into strings for printing. So the following is correct:

```
print ("The circumference is ", 62.831852)
```

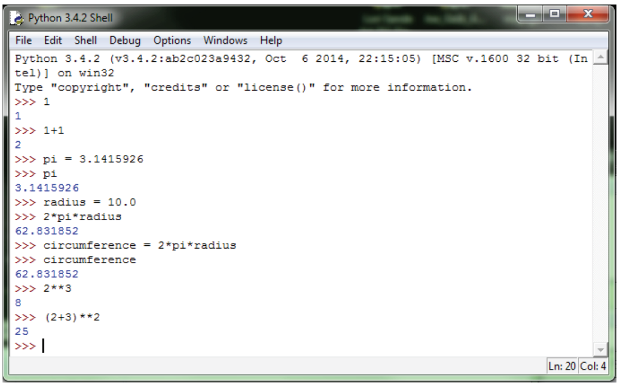


Figure 1.3
The Python GUI window with an example.

If a variable appears in the list following print then the value of that variable will be printed, not the name of the variable. Therefore, the following is also correct:

```
print ("The circumference is", circumference)
```

1.6.3 Example 1: Draw a Circle Using Characters

Let's print a circle with a constant predefined radius. This can be done with a few print statements. The planning of the graphic itself (the circle) can be done using graph paper. Assuming that each character uses the same amount of space, a circle can be approximated using some skillfully placed * characters. Then, we print each row of characters using a print statement. A sample solution is shown in Figure 1.4.

```
print ("       ***         ")
print ("    *********      ")
print ("  *************    ")
print (" ***************   ")
print (" ***************   ")
print (" ***************   ")
print ("  *************    ")
print ("    *********      ")
print ("       ***         ")
```

Figure 1.4
Drawing a circle using *print* statements.

1.6.4 Strings, Integers, and Real Numbers

Computer programs deal mainly with numbers. Integers, or whole numbers, and real number (reals) or floating-point numbers, which represent fractions, are represented differently and arithmetic works differently on the two types of numbers. A Python variable can hold either type, but if a variable contains an integer, then it is treated as an integer, and if it's holding a floating-point number, then it is treated as one of those. What's the difference? First, there's a difference in how they are printed out. If we make the assignment **var = 1** and then print the value of **var**, it prints simply as 1. If we make the assignment **var = 1.0** and then print **var**, it prints as 1.0. In both cases **var** is a real or floating-point number and is treated as such. Numeric constants are considered real numbers. However, a variable can be first one thing and then another. It will be the last thing it was assigned.

Arithmetic differs between integers and reals, but the only time that difference is really apparent is when doing division. Integers are always whole, non-fractional numbers. If we divide 3 by 2, both 3 and 2 are integers and so the division must result in an integer: the result is 1. This is because there is exactly a single 2 in 3, or if you like, 2 goes into 3 just once, with a remainder of 1. There is a specific operator for doing integer division: //. So, 3//2 is equal to 1. The remainder part can't be handled and is discarded, but can be found separately using the % operator. For example, 8//5 is 1, and 8%5 is the remainder, 3. This explanation is an approximation to the truth, and one that can be cleared up later, but works perfectly well for positive numbers.

Of course, fractions work fine for real numbers, and are printed as decimal fractions: 8.0/5.0 is 1.6, for example. What happens if we mix real numbers and integers? In those cases, numbers get converted into real numbers, but now things get more complicated because order can matter a great deal. The expression 7//2*2.0 does the division 7//2 first, which is 3, and then multiplies that by 2.0, yielding the result 6.0; the result of 8/3*3.0 is 5.333. Mixing integers and real numbers is not a good idea, but if done, then the expressions should use parentheses to specify how the expression should be evaluated.

A real number can be used in place of an integer in most places, but the result is a real number. Thus, 2.0 * 3 = 6.0, not 6, and 6.0//2 is 3.0, not 3. There are some exceptions. To convert an integer to a real number, there is a special operation named **float**: **float(3)** yields 3.0. Of course, it's possible to simply multiply by 1.0, and the result is a floating value, too. Converting float values to integers is more complicated because of the fraction issue: what happens to the digits to the right of the decimal? The operation **int** takes a floating-point value and throws away the fraction. The value of **int (3.5)** is 3, as a result. We can round this to the nearest integer, and the operation **round (3.5)** does that, resulting in 4.

1.6.5 Number Bases

In elementary school, the idea of positional number systems is taught. The number 216 is a way to write the value of 6 + 1*10 + 2*100. Not all civilizations use such a scheme; Roman numerals are not positional, for example. Still, most people are comfortable with the idea. What people are not as comfortable with is changing the number base away from 10. In Chapter 0, the binary system, or base 2, was discussed, but any base that is a power of 2 is of some interest, especially base 8 and base 16.

Humans use a base 10 scheme (probably because we have 10 fingers). We have a symbol for each of the 10 digits, 0 through 9, and each digit position to the left of the first digit is multiplied by the next power of 10. The number 216 is $2*10^2 + 1*10^1 + 6*10^0$. The base is 10, and each digit represents a power of the base multiplied by a digit. What if the base is 8? In that case, 216 is really $2*8^2 + 1*8^1 + 6$. If the arithmetic is carried out, this number is 128+8+6 = 142.

If multiple number bases are used, it is common to give the base as a subscript. The number 216 in base 8 is written as 216_8. The default would be base 10. In base 8, there are only 8 digits, 0 through 7. The digits 8 and 9 cannot appear. In bases larger than 10, more symbols are needed. A common base used on computers is 16, or hexadecimal (hex for short). In a hex number, 16 digits are needed, so the regular ones are used and then "A" represents 10, "B" is 11, "C" is 12, "D" is 13, "E" is 14, and "F" is 15. The hex number 12_{16} is 1*16 + 2, or 18_{10}. The number $1A_{16}$ is 1*16 + 10 = 26_{10}.

In Python, numbers are given in decimal (base 10) by default. However, if a number constant begins with "0o" (zero followed by the letter "o"), Python assumes it is base 8 (octal). The number **0o21**, for example, is $21_8 = 17_{10}$. A number that begins with "0x" is hexadecimal. **0x21** is $21_{16} = 33_{10}$. This applies only to integers.

Base 2 is the most important number base because it underlies all of the numbers on a computer. All numbers on a modern digital computer are represented in base 2, or binary, in their internal representation. A binary number has only two digits, 0 and 1, and each represents a power of 2. Thus, 1101_2 is $1*2^3 + 1*2^2 + 0*2^1 + 1 = 8 + 4 + 1 = 13_{10}$. In Python, a binary number begins with "0b," so the number **0b10101** represents 21_{10}.

These number bases are important for many reasons, but base 2 is fundamental, and bases 8 and 16 are important because they are powers of 2 and so convert very easily to binary but have fewer digits. One example of the use of hex is for colors. In Python, they can represent a color, and on Web pages they are certainly used that way. The number 0xFF0000 is the color red, for example, if used on a Web page.

1.6.6 Example 2: Compute the Circumference of Any Circle

When humans input information into a computer program, the text tends to be in the form of numbers. The Python code that was written to calculate the radius of a circle only did the calculation for a single radius: 10. That's not as useful as a program that computes the circumference of any circle, and that would mean allowing the user to tell the program what radius to use. This should be easy to do, because it is something that is needed frequently. In the case of sending a number into a program in Python, the word **input** can used within a program. For example,

```
radius = input ()
```

accepts a number from the keyboard, typed by the user, and returns it as a string of characters. This makes sense because the user typed it as a string of characters, but it can't be used in a calculation in this form. To convert it into the internal form of a number, we must specifically ask for this to be done:

```
radius = input()
radius = float(radius)
```

reads a string into **radius**, then converts it into a floating point (real) number and assigns it to the variable **radius** again. This can be done all in one statement:

```
radius = float(input())
```

Now the variable radius can be used to calculate a circumference. If the value of **radius** is an integer, the code is as follows:

```
radius = int(input())
```

If the conversion to a number is not done then Python will give an error message when the calculation is performed, like:

```
Traceback (most recent call last):
  File "<pyshell#13>", line 1, in <module>
    circumference = 2*pi*radius
TypeError: can't multiply sequence by non-int of
type 'float'
```

The line of code at which the error occurs is given and the term *TypeError* is descriptive. This error means that something that can't be multiplied (a string) was used in an expression involving multiplication. That thing is the variable **radius** in this instance because it was and text string and was not converted to a number.

Note that **int(input())** can present problems when the input string is not an integer. If it is a floating-point number, this results in an error. The expression **int (“3.14159”)** is interpreted as an attempt convert *pi* into an integer, and so has the value 3 (which is erroneous). The function **int** was passed a string and the string contained a float, not an integer. This is something of a quirk of Python. It is better to convert input numbers into floats.

1.6.7 Guess a Number Again

The simple version of the guessing program can now nearly be written in Python. Examining the method of solution, here’s what can be coded so far; versions depend on who is guessing. The computer should pick the number and the human user should guess, because the other way around can involve some complex programming. In that case, here’s what has to happen:

1. The computer selects a number.
   ```
   choice = 7
   ```
2. The computer asks the player to guess.
   ```
   print ("Please guess a number between 1 and 10: ")
   ```
3. The player types a number on the keyboard and the computer reads it in.
   ```
   playerchoice = input()
   ```
4. The computer compares the input number against the one that it selected and if the two agree, then the player wins. Otherwise the computer wins.

It is the final step that is still not possible with what is known. It is necessary in this program, as it is in most computer programs, to make a decision and to execute certain code (i.e., do specific things) conditionally based on the outcome of that decision. People do that sort of thing all of the time in real life. Examples include the following:

“If the light is red, then stop; otherwise continue through the intersection.”

“If all tellers are busy when you arrive at the bank, then stand in line and wait for the next one to become available.”

“If you need bread or milk, then stop at the grocery store on the way home.”

“If it rains, the picnic will be cancelled.”

Notice that all of these examples use the word "if." This word indicates a standard *conditional sentence* in English. The condition in the first case is the phrase "if the light is red" (called in English the *protasis* or *antecedent*) and the consequence to that is the phrase "then stop" (the *apodosis* or *consequent*). Terminology aside, the intent is clear to an English speaker: on the condition that or in the event that the light is red, then the necessary action is that the driver is to stop their car. The action is conditional on the antecedent, which in Python is called an *expression* or more precisely a *logical expression*, which has the value True or False.

The structure or syntax of this sort of thing in Python is as follows:

```
if the light is red:
   stop
```

or more exactly,

```
   if light == red:
         # execute whatever code makes the car stop
```

This is called an **if** statement.

1.7 IF STATEMENTS

An if statement begins with the word **if**, followed by an expression that evaluates to **True** or **False**, followed by a colon (**:**), then a series of statements that are executed if the expression is true. The names True and False are constants having the obvious meaning, and a variable that can take on these values is a *logical* or *Boolean* (named after the man who invented two state or logical algebra) variable. The expression is the only tricky part. It can be a constant like **True**, or a variable that has a **True** or **False** value, or a *relational expression* (one that compares two things) or a logical combination of any of these – anything that has a result that is true or false.

```
if True:                  # Constant
if flag:                  # Logical variable
if a < b:                 # relational expression
if a<b and c>d:           # logical combination
```

A logical expression can be any arithmetic expressions being compared using any of the following operators:

< Less than

> Greater than

<= Less than or equal to

>= Greater than or equal to

== Equal to

!= Not equal to

Logical combinations can be:

and EG: a==b and b==c

or EG: a==b or a==c

not EG: not (a == b) # same as !=

The syntax is simple and yet allows a huge number of combinations. For example,

```
if p == q and not p ==z and not z == p:
if pi**2 < 12:
if (a**b)**(c-d)/3 <= z**3:
```

The *consequent*, or the actions to be taken if the logical expression is true, follows the colon on the following lines. The next statement is indented more than the **if**, and all statements that follow immediately that have the same indentation are a part of the consequent and are executed if the condition is true, otherwise none of them are. As an example, consider the following:

```
if a < b:
    a = a + 1
    b = b - 1
c = a - b
```

if	a<b	:
The key word, known by Python, that indicates this is an IF statement.	An expression that evaluates to **True** or **False**	The colon indicates the end of the first part of the statement. Think of it as meaning **THEN**, as in **IF expression THEN**

Figure 1.5
Syntax of an IF statement.

In this case, the two statements following the ":" are indented by 4 more spaces than is the **if**. This tells Python that they are both a part of the **if** statement, and that if the value of **a** is smaller than the value of **b,** then both of those statements will be executed. Python calls such a group of statements a *suite*. The assignment to the variable **c** is indented to the same level as the **if**, so it will be executed in any case and is not conditional.

The use of indentation to connect statements into groups is unusual in programming languages. Most languages in use ignore spaces and line breaks altogether, and use a statement separator, such as a semicolon, to demark statements. So, in the *Java* language, the above code is as follows:

```
if (a<b) {
  a = a + 1;
  b = b - 1;
}
c = a - b;
```

The braces { … } enclose the suite, which would probably be called a *block* in Java or C++. Notice that this code is also indented, but in Java this means nothing to the computer. Indentation is used for clarity, so that someone reading the code later can see more clearly what is happening.

Semicolons are used in Python too. If it is desired to place more than one statement on a single line, then semicolons can be used to separate them. The Python **if** statement under consideration here could be written as follows:

```
if a < b: a = a + 1; b = b -1
c = a - b
```

This is harder to comprehend quickly and is therefore less desirable. There are too many symbols all grouped together. A program that is easy to read is also easier to modify and maintain. Code is written for computers to execute, but is also for humans to read.

There are some special assignment operators that can be used for incrementing and decrementing variables. In the above code, the statement **a = a + 1** could be written as **a += 1**, and **b = b – 1** can be written as **b -= 1**. There is no real advantage to doing this, but other languages permit it, so Python adopted it too. There is another syntax that can be used to simplify certain code in languages like Java and C, and that is the increment operator "++" and the decrement operator "—". Python does not have these. However, an effect of the way that Python deals with variables and expressions is that **++x** is legal; so is **++++x**. The value is simply **x**. The expression **x++** is not correct.

1.7.1 Else

An **if** statement is a two-way or binary decision. If the expression is true, then the indicated statements are executed. If it is not true, then it is possible to execute a distinct set of statements. This is needed for the *pick a number* program. In one case, the computer wins, and in the other, the human wins. An *else* clause is what will allow this.

The else is not really a statement on its own, because it has to be preceded by an **if**, so it's part of the **if** statement. It marks the part of the statement that is executed only when the condition in the **if** statement is false. It consists of the word **else** followed by a colon, followed by a suite (sequence of indented statements). A trivial example is as follows:

```
if True:
   print ("The condition was true")
else:
   print ("the condition was false")
```

The **else** as a clause is not required to accomplish any specific programming goals, and can be implemented using another **if**. The code

```
   if a < b:
         print ("a < b")
else:
         print ("a >= b")
```

could also be written as

```
   if a < b:
         print ("a < b")
if  not (a<b):
         print ("a >= b")
```

The **else** is *expressive*, *efficient*, and *syntactically convenient*. It is expressive because it represents a way that humans actually communicate. The word *else* means pretty much the same thing in Python as it does in English. It is efficient because it avoids evaluating the same expression twice, which costs something in terms of execution speed. It is syntactically convenient because it expresses an important element of the language in fewer symbols than when two **if**s are used.

The final Python code for the simple solution of the guess a number program can now be written.

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())

      if choice == playerchoice:
           print ("You win!")
      else:
           print ("Sorry, you lose.")
```

1.8 DOCUMENTATION

There are some problems with this program, but is does work. A large problem is that it always choses the same number every time it is executed (that number is 7). We will fix this issue later on. A less critical problem is that the program is *undocumented*; that is, there are no instructions to a player concerning how to use the program, and there is no description of how the program works that another programmer might use if modifying this code. This can be fixed by providing *internal* and *external* documentation.

External documentation is like a manual for the user. Most programs have such a thing, and even though this program is quite simple, some degree of documentation can be provided. In fact, it is brief enough that it could be printed whenever the program starts to run.

```
print ("Pick-a-number is a simple guessing game. The")
print ("computer will select a number between 1 and 10").
print ("and you are expected to guess what it is.")
print ("When the program displays 'Please guess")
print ("a number between 1 and 10: ' you type in")
print ("your guess followed by the <enter> key. Your ")
print ("guess must be an integer in the range 1 to 10.")
print ("The computer will tell you if you win or lose.)
```

For many more sophisticated programs, such as *PowerPoint*, the documentation is many pages and forms a small book. It is distributed as a booklet along with the software or provided as a website.

Internal documentation is intended for programmers who have access to the source code of the program. It can take the form of written documents, too, but is commonly a set of comments that appears along with the code itself. High-level languages like Python allow the programmer to add human language text to the code that will be completely ignored by the computer, but that can be read by anyone looking at the code. These comments describe the action of the program, the meaning of the variables, details of computational methods used, and many other items of interest.

A comment begins with the character # and ends at the end of the line.

There are no rules for what can appear typed in a comment, but there are some guidelines developed through years of programming practice. A comment should not simply repeat what appears in the code, a comment explain an aspect of the program that might not be clear to a person looking at it, and it should be written in plain language. As an example, here is the *guess-a-number* program with comments included:

```
# This program selects a number between 1 and
# 10 and allows a user (player) to guess what
# it is.
choice = 7   # The number selected by the computer

# Prompt the user, indicating what is expected
print ("Please guess a number between 1 and 10: ")

# Read the player's input from the keyboard
playerchoice = int(input()) # convert from string

     # Print the outcome of the game.
if choice == playerchoice:  # Is the player's guess
    print ("You win!")      # correct? Player wins!
else:                       # Otherwise the computer wins
    print ("Sorry, you lose.")
```

All programs should be documented as they are being written because relatively few programs are written all in one sitting. The comments in the code serve as reminders to the programmer about what the variables represent and why particular code segments read the way they do. It also indicates the current state of thinking about the design of the code. When the program is looked at again at the beginning of a new working (or school) day, the comments can be essential in resuming the work.

There is also something called a *docstring* that seems to do the same things as a comment, but covers multiple lines and is not really a comment. A *docstring* begins and ends with a triple quote:

```
print ("This code will execute")
"""
print ("This code is within a docstring")
"""
```

A *docstring* is actually a string, not a comment, but behaves like a comment and can be used in that way. It can be especially useful for temporarily commenting out small sections of code while trying to find out where errors are. There are also programs that collect the *docstrings* into a separate document that can be used as a description of the program. Their intended use is to allow the programmer to explain the purpose of certain sections of code.

1.9 ROCK-PAPER-SCISSORS AGAIN

It is time to look at the rock-paper-scissors problem and see if it can be coded. It takes more steps, but it is no more complicated than the guess-a-number program. The code is the same.

1. Select a choice from the three items rock, paper, or scissors. Save this choice in a variable named **choice**.

   A representation for the three items was when the solution was first described, where each choice was an integer. However, **input** reads strings so it should be possible to avoid the conversion to numbers and use the strings directly.

   ```
   choice = "paper"  # Computer chooses paper.
   ```

   Ask the player for their choice.

   Print as prompt message.

   ```
   print ("Rock-paper-scissors: type in your choice:   ")
   ```

2. Read the player's selection into a variable named **player.**

   Use **input** as we did before, but this time read a string and keep it that way. The player must type one of "rock," "paper," or "scissors," or else an error is reported.

   ```
   player = input ()
   ```

3. If **player** is equal to **choice**:
4. Print the message "Tie. We'll try again."

   Strings can be compared against each other for equality, so this step is quite simple:

   ```
   if player == choice:
       print ("Game is a tie. Please try again.")
   ```

5. If **player** is equal to rock
6. If **choice** is equal to scissors, go to Step 17.
7. There is no "go to Step 17," but that step simply says that the player wins. Just print that message here.

```
if player == "rock":
    if choice == "scissors":
      print ("Congratulations. You win.")
    else:
      print ("Sorry - computer wins.")
```

8. If **player** is equal to paper
9. If **choice** is equal to scissors, go to Step 17.

```
if player == "paper":
    if choice == "scissors":
        print ("Sorry - computer wins.")
    else:
        print ("Congratulations. You win.")
```

10. If **player** is equal to scissors
11. If **choice** is equal to rock, go to Step 17.

```
if player == "scissors":
    if choice == "rock":
        print ("Sorry - computer wins.")
    else:
        print ("Congratulations. You win.")
```

This code illustrates a new concept, if not a new language feature. It has **if** statements that are nested one within the other. Again, it's not necessary to do this because non-nested statements can implement the same decision. For example,

Nested **IF**s

```
if player == "scissors":

    if choice == "rock":
      print ("Computer wins.")

    else:
      print ("You win.")
```

Non-nested **IF**s

```
if player == "scissors and
             choice == "rock"
    print ("Computer wins")
if player == "scissors" and
             choice != "rock"
    print ("You win")
```

Nested if statements seem more express ive and communicate the flow of the program better to a human programmer than does the non-nested code.

There is another Python language element that can be used here. Looking at the code, there is no indication when the user makes an error. For example, if the user enters “ROCK” (i.e., all in uppercase letters), then it will not match any of the choices and the program will not indicate this. In fact, it won’t print anything at all. What is really wanted is a sequence of **if-else-if-else** statements such as

```
if player == "scissors":
    if choice == "rock":
else:
    if player == "rock":
        if choice == paper:
    else:
        if player == "scissors":
   ## and so on …
```

Python has a special feature that implements this nesting of **if** and **else**: the **elif**. The **elif** construct combines an **else** and an **if**, and this reduces the amount of indenting that has to be done. The following code snippets do the same thing:

```
if a<b:
    print ("a<b")
elif a>b:
    print ("a>b")
else:
    print ("a=b")
```

```
if a<b:
print ("a<b")
else:
if (a>b):
      print ("a>b")
else:
      print ("a=b")
```

If too many nested if-else statements exist, then the indenting becomes too challenging, whereas the **elif** allows the same indent level and has the same meaning. In some programs, this is essential, and in general, it is easy to read. Using the **elif** statement the program for the *rock-paper-scissors* problem looks like this:

```
choice = "paper"  # Computer chooses paper.
print ("Rock-paper-scissors: type in your choice:    ")
player = input ()
if player == choice:
    print ("Game is a tie. Please try again.")
if player == "rock":
    if choice == "scissors":
```

```
            print ("Congratulations. You win.")
     else:
            print ("Sorry - computer wins.")
    elif player == "paper":
        if choice == "scissors":
            print ("Sorry - computer wins.")
        else:
            print ("Congratulations. You win.")
    elif player == "scissors":
        if choice == "rock":
            print ("Sorry - computer wins.")
        else:
            print ("Congratulations. You win.")
    else:
       print ("Error: Select one of: rock, paper, scissors")
```

Now all of the possible outcomes are handled by the code.

1.10 TYPES ARE DYNAMIC (*ADVANCED*)

To programmers who only program using Python, it would seem odd that a particular variable could have only one type and that it would have to be initially defined to have that type, but it is true. In Python, the type associated with a variable can change. For example, consider the statements:

```
x = 10                # X is an integer
x = x*0.1             # X is floating point now
x = (x*10 == 10)      # X is Boolean
```

Some find this perfectly logical, and others find it confusing. As the variable is used according to its current type, all will be well.

Even simple Python types can be complex in terms of their implementation. A programmer rarely needs to know about the underlying details of types like *integers*. In many programming languages, an integer is simply a one- or two-word number, and the languages build operations like + from the instruction set of the computer. If, for example, a one-word integer A is added to another one B, it can be done using a single computer instruction like ADD A, B. This is very fast at execution time.

Python was designed to be convenient for the programmer, not fast. An integer is actually a complex object that has attributes and operations. This will become clearer as more Python examples are written and understood, but as a simple case, think about the way that C++ represents an integer. It is a 32-bit (4 byte) memory location, which is a fixed size space in memory. The largest number that can be stored there is 2^{32}-1. Is that true in Python?

Here's a program that will answer that question, although it uses more advanced features:

```
for i in range (0,65):
    print (i, 2**i)
```

Even an especially long integer is less than 65 bits. This program runs successfully and quickly. Integers in Python have an arbitrarily large size. Calculating $2^{64} * 2^{64}$ is possible and results in 340282366920938463463374607431768211 456. This is very handy indeed from a programmer's perspective.

The type of a variable can be determined by the programmer as the program executes. The function **type ()** returns the type of its parameter as a string, and it can be printed or tested. So, the code

```
z = 1
print (type(z))
z = 1.0
print(type(z))
```

will result in

```
<class 'int'>
<class 'float'>
```

If one needed to know if **z** was a float at a particular moment, then

```
if type(z)is float:
```

would do the trick. **Type(z)** does not return a string, it returns a *type*. The **print ()** function recognizes that and prints a string, just as it does for **True** and **False**. So

```
if type(z) == "<class 'float'>":
```

would be incorrect.

In future chapters, this malleability of types will be further described, and practical methods for taking advantage of it in Python will be examined.

1.11 SUMMARY

A computer is a tool for rapidly and accurately manipulating numbers. It can perform tedious repetitive tasks accurately and quickly, but must be told what to do and follows its instructions very literally. A computer program is a set of instructions for performing a task using a computer, and Python is one language that can be used for this purpose. Python allows a programmer to define variables by simply using them, and associates a type with a variable based on what it is given. An **if** statement allows parts of a program to be executed when a certain condition becomes true, and it can have an **else** part that is executed when the condition is false. **If** statements can be nested, and sometimes the **elif** structure is a good way to express a set of nested conditional code.

In this chapter, the main examples were two programs, one of which allowed a user to guess a number, while the other was the well-known game of *rock-paper-scissors*.

Exercises

In the following exercises, some of the expressions may result in an error. If so, explain why the error occurs. The code should be Python 3.

1. Evaluate the following expressions:

a) `3*3/2`

b) `3*3//2`

c) `3*3%2`

d) `(3*3)%2`

e) `3**3/3`

f) `(3+2)-(2-4)`

g) `(3+2)/(2-4)`

2. If the statements:

```
x = 3
y = 9
z = "2.4"
```

have been executed, then evaluate the following expressions. If an error occurs, state why:

```
x/y
x//y
x%y
y/x*z
float(x)/float(z)
float(x)//float(z)
int(x)//int(z)
```

3. Given the variable definitions presented, evaluate the following expressions as being **True** or **False**.

```
x = 12
y = 14
```

a) `x>3`

b) `x >=12`

c) `x<y`

d) `x<y and y>14`

e) `x<y  or  y>14`

f) `not (x == y)j34`

g) `not(x<y) and not(y>14)`

4. What is printed with the following statements?

a) `print (int("23"))`

b)
```
if 3**2+4**2 == 5**2:
     print ("345")
elif 3**2 < 4**2:
     print ("34")
else:
     print ("5")
```

c)
```
if "toast" < "jam":
     print ("toast")
else:
     print ("jam")
```

d)
```
if "12" < "5":
  print ("12")
else:
  print ("5")
```

e)
```
a = 12.3
b = 100
c = 0
if a < b: a = a + 1; b = b -1
c = c - b
print (a)
print (c)
```

f)
```
a = 100
b = 200
c = 300
ab = a<b
cd = (c == a+b)
if ab and cd:
    print ("AB and CD")
elif ab:
    print ("AB")
else:
    print ("Nope")
```

5. The United States measures temperature in Fahrenheit degrees, whereas Canada uses Celsius. A company is developing an app to convert between the two for people wanting to ski in Banff or Whistler. The formula to convert from Celsius degrees C to Fahrenheit degrees **F** is

```
F = C*9/5 + 32
```

Write a program that will be the basis of this app: it will read a temperature in Celsius, convert it to Fahrenheit, and print the result.

6. The numerical values of coins have been arranged so that the *greedy algorithm* will result in the smallest number of coins when making change. This means that the largest valued coin is tried first, and as many of those coins are used as possible. Then the next smaller denomination coin is used, and so on until the pennies are dealt out. For **84** cents in change, a half-dollar could be used (leaving 34 cents), then a quarter (leaving 9 cents), a nickel (leaving 4 cents), and 4 pennies. If no half-dollar coin was available, then quarters would be used in its place: 3 quarters, followed by a nickel and four pennies. Write a program that reads a number between 1 and 99 that is an amount of change to be given, and prints the coin values that would be used.

a) Three floating point variables **a**, **b**, and **c** have been read in from the console. Write a set of **if** statements that prints these in descending order.

b) If the value of 1.0/7.0 is printed, there are many numbers to the right of the decimal place. Devise a way to print only three places and write some Python code to test the idea.

c) Calculate an approximation to pi. There is an infinite series called the *Gregory-Leibniz* series that sums to pi. The series is

$$\Pi = 4/1 - 4/3 + 4/5 - 4/7 + 4/9 - 4/11 \ldots.$$

Write a program that calculates the result of the first 15 terms of this series. How many digits of pi are correct? Add six more terms. How many digits are correct now?

d) Another series that can calculate pi is the *Nilakantha* series. It is a little more complicated to calculate, but gets close to pi much faster than does the *Gregory-Leibniz* series of Exercise 9. The *Nilakantha* series is

$$\Pi = 3 + 4/(2*3*4) - 4/(4*5*6) + 4/(6*7*8) - 4/(8*9*10) \ldots$$

Calculate the first 15 terms of this series. How many digits of PI are correct?

Notes and Other Resources

Many teaching resources for Python exist, both in print and on the Internet.

Here is the development environment used to test the code for this book,

PyCharm: *https://www.jetbrains.com/pycharm/*

1. David Beazley and Brian K. Jones, *Python Cookbook, 3rd Edition: Recipes for Mastering Python 3*, http://www.onlineprogrammingbooks.com/python-cookbook-third-edition/
2. Cody Jackson, *Learning to Program Using Python*, http://www.onlineprogrammingbooks.com/learning-program-using-python/
3. Brad Miller, *Problem Solving with Algorithms and Data Structures Using Python*, http://www.onlineprogrammingbooks.com/problem-solving-with-algorithms-and-data-structures/
4. Harry Percival, *Test-Driven Development with Python*, http://www.onlineprogrammingbooks.com/test-driven-development-with-python/
5. *Lennart Regebro, Porting to Python 3*: An in-depth guide, http://www.onlineprogrammingbooks.com/porting-to-python-3-an-in-depth-guide/
6. Zed A. Shaw, *Learn Python the Hard Way*. http://learnpythonthehardway.org/book/

Chapter 2

Repetition

In this chapter

One of the things that makes computers attractive to humans is their ability to do tedious, repetitive tasks accurately and at high speed without getting bored. In programming terms, these actions are referred to as *loops*.

Consider a factory job on an assembly line. According to Henry Ford, made famous by his assembly line concept, it is more efficient to have each worker do one job well and repeat it many times a day than to teach workers how to build entire things (in his case, automobiles). Each worker does one relatively short job, and then the piece they are working on goes to the next station, where the next person does their relatively short job. One such job could be the installation of the electronic ignition module bracket. The instructions might be like this:

1. Acquire a bracket and place over attachment holes with the wide end below the smaller end.
2. Place a two-inch bolt in the upper-left bolt hole and screw in to two pounds of torque.
3. Place a four-inch bolt in the upper-right bolt hole and screw in to two pounds of torque.
4. Place a two-inch bolt in the lower-left bolt hole and screw in to two pounds of torque.
5. Place a ten-millimeter nut over the bolt at the lower right and tighten to ten pounds.
6. Re-tighten the bolts to ten pounds in the following order: upper left, upper right, and lower left.

Before Step 1 above, a new work piece (an engine, probably) is placed in front of the worker, and after Step 6, the piece is moved to the next station. From the worker's perspective, *so long as* or *while* there is an engine at their station that needs a bracket, they repeat the steps. In a form that a computer might be able to understand, this might be written as:

while there is an engine at their station that needs a bracket**,**

Acquire a bracket and place it over the attachment holes with the wide end below the smaller end.

Place a two-inch bolt in the upper-left bolt hole and screw in to two pounds of torque.

Place a four-inch bolt in the upper-right bolt hole and screw in to two pounds of torque.

Place a two-inch bolt in the lower-left bolt hole and screw in to two pounds of torque.

Place a ten-millimeter nut over the bolt at the lower right and tighten it to ten pounds of torque.

Re-tighten the bolts to ten pounds of torque in the following order: upper left, upper right, and lower left.

All of the actions that follow the **while** are indented to indicate that they are a part of the activities to be repeated, just as was done in a Python **if** statement to mark the things that were to be done if the condition was true. This example illustrates one of the Python repetition structures quite accurately: the **while** statement.

while	a<b	:
The key word, known by Python, that indicates that this is a **WHILE** statement.	An expression that evaluates to **True** or **False**	The colon indicates the end of the first part of the statement. Think of it as meaning **DO** as in **WHILE expression DO**

Figure 2.1
Essential syntax of the WHILE statement.

2.1 THE WHILE STATEMENT

When using this repetition statement, the condition is tested at the top or beginning of the loop. If, upon that initial test, the condition is true, then the body of the loop is executed; otherwise, it is not, and the statement following the loop is executed. This means that it is possible that the code in the loop is not executed at all. The condition tested is the same kind of expression that is evaluated in an **if** statement: one that evaluates to **True** or **False**. It could be, and often is, a comparison between two numeric or string values, as it is in the example of Figure 2.1.

When the code in the body of the **while** statement has been executed, then the condition is tested again. If it is still true, then the body of the loop is executed again, otherwise the loop is exited and the statement following the loop is executed. There is an implication in this description that the body of the loop must change something that is used in the evaluation of the loop condition, otherwise the condition will always be the same and the loop will never terminate. Here is an example of a loop that is entered and terminates:

```
a = 0
b = 0
while a < 10:
      a = a + 1
print (a)
```

The condition **a<10** is true at the outset because **a** has the value 0, so the code in the loop is executed. The lone statement in this loop increments **a**, so that after the first time the loop is executed the value of **a** is 1. Now the condition is tested and, again, **a<10**, so the loop executes again. In the final iteration of the loop, the value of **a** starts out as 9, is incremented, and becomes 10. When the condition is tested it fails, because **a** is no longer less than 10 (it is equal) and so the loop ends. The statement following the loop is **print (a)** and the value printed is 10. This loop explicitly modifies one of the variables in the loop condition, and it is easy to see that the loop will end and what the value of **a** will be at that time.

Here is an example of a loop that is entered and does *not* terminate:

```
a = 0
b = 0
while b < 10:
      a = a + 1
print (a)
```

In this case, the value of **b** is less than 10 at the outset, so the loop is entered. The body of the loop increments **a** as before, but does not change **b**. The loop condition does not depend on **a**, only on **b**, so when the loop condition is tested again, the value of **b** is still 0, and the loop executes again. The value of **b** will always be 0 each time it is tested, so the loop condition will always be true and the loop will never end. The print statement will never be executed.

When this program is executed, the computer will seem to become unresponsive. As long as the loop is executing the program can do nothing else, and so the only indication that something is wrong is that nothing is happening. There are many reasons why a program can appear to be doing nothing: when waiting for the user to type some input, for instance, or when performing an especially difficult calculation. However, in this case, which is called an *infinite loop*, the only thing to do is to terminate the program and fix the loop.

Here is an example of a loop that is not entered:

```
a = 100
b = 0
while a < 10:
      a = a + 1
print (a)
```

The condition **a<10** is false at the outset because **a** has the value 100, so the code in the loop is not executed. The statement following the loop is executed next, which is the print statement, and the value printed is 100.

These loops are examples that illustrate the three possibilities for a **while** loop and do not calculate anything useful. The two examples from the previous chapter can make practical use of a while loop, and it would be useful to look at those again.

2.1.1 The Guess-A-Number Program Revisited

The program as it was written in Chapter 1 is as follows:

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())
if choice == playerchoice:
      print ("You win!")
else:
      print ("Sorry, You lose.")
```

The game would be better if it allowed the player to guess again, perhaps until a correct guess was achieved. A while loop could be used to accomplish this. Think about what the condition might be. The loop should end when the player guesses the answer. Another way to say this is that the loop should *continue* so long as the player has *not* guessed the answer. The condition is one for continuation of the loop, not termination, so the loop must be constructed in such a way that it continues when the condition is true. The loop will begin with this:

```
while choice != playerchoice:
```

At the beginning of the loop, the variables **choice** and **playerchoice** must be defined. This means that before the while statement there must be code that does this. The program now looks like this:

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())
while choice != playerchoice:
```

If the player has guessed incorrectly, then the body of the loop will execute. What should be done? One of the variables in the condition has to be changed, and the goal of the program must be kept in mind. In this case, because the player has guessed incorrectly, two things should happen. First, the player must be told that they are wrong and to make another guess. Next, the new guess must be read into the variable **playerchoice**, thus satisfying the rule that the loop condition must possibly have an opportunity to become False. The program is now

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())
while choice != playerchoice:
      print ("Sorry, not correct. Guess again: ")
      playerchoice = int(input())
```

When the player finally guesses the number, the loop will exit; if the first guess is correct, then the condition fails at the beginning, and this amounts to the same thing in this case. The last thing to do is to print a message to the player:

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())
while choice != playerchoice:
   print ("Sorry, not correct. Guess again: ")
   playerchoice = int(input())
print ("You have guessed correctly.")
```

Note that, as was true with the **if** statement and as is always true in Python, the indentation indicates which statements are a part of the loop (the *suite*) and which are outside.

2.1.2 Modifying the Game

A simple modification of the game involves telling the player whether their guess was too large or too small. This will help them shrink the possible range of values and thus guess the right answer more quickly. A modification to the body of the loop will accomplish this. If the value that the player guessed is smaller than the target, then a message to that effect is printed, and similarly if the player guesses a value larger than the target. The use of an **if** statement here is appropriate, and that if statement is nested inside of the **while** loop:

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())
while choice != playerchoice:
    if (playerchoice < choice):
        print ("Sorry, your guess was too small.
                  Guess again: ")
```

```
    else:
        print ("Sorry, your guess was too large.
                  Guess again.")
    playerchoice = int(input())
    print ("You have guessed correctly.")
```

This program illustrates a second level of indentation. The **if-else** are indented to indicate they are part of the **while** statement. The **print** statements are indented further, to show that they are also part of the **if** statement.

Doing some printing inside of the loop is useful because an infinite loop will be obvious. It will print many lines and never stop. It's not always practical to do that, so a degree of careful analysis should always be done to ensure that the loop can and will terminate.

2.2 ROCK–PAPER–SCISSORS REVISITED

This game needs a loop, and the previous implementation was not complete. If there is a tie, then the game has to be repeated, and a winner must be determined. This means that the loop in this case is as follows:

```
while there is no winner:
```

This happens only when the player and the computer select the same object, and in the original code, it was handled by the statements:

```
if player == choice:
    print ("Game is a tie. Please try again.")
```

The condition "no winner" becomes **player == choice**. The complete solution involves the **while** loop and another input from the user within the loop. Here is one possible answer:

```
choice = "paper"  # Computer chooses paper.
print ("Rock-paper-scissors: type in your choice:    ")
player = input ()

# --------- The new section of code ---------------------
while player == choice:   # Repeat input until there is a
                                 winner
    print ("Game is a tie. Please try again.")
    player = input ()
# ---------------------------------------------------------
```

```
if player == "rock":
    if choice == "scissors":
        print ("Congratulations. You win.")
    else:
        print ("Sorry - computer wins.")
elif player == "paper":
    if choice == "scissors":
        print ("Sorry - computer wins.")
    else:
        print ("Congratulations. You win.")
elif player == "scissors":
    if choice == "rock":
        print ("Sorry - computer wins.")
    else:
        print ("Congratulations. You win.")
else:
    print ("Error: Select one of: rock, paper, scissors")
```

The termination of the loop depends on the user's input, and on the value of the computer's choice, which could also (and should) change inside the loop. The probability of the loop continuing after one iteration is 1 in 3, and the probability that it will still be looping after N iterations is $(1/3)^N$, so there is a very small chance of the loop repeating more than 2 or 3 times.

2.2.1 Random Numbers

Most games depend on an element of unpredictability or chance. Those that do not might be more properly called *puzzles*. Given that computers do calculations, and that calculations should have the same result every time, how does one produce anything that is *random* using a computer? The answer is partly in how the term random is defined. The discussion involves some mathematics or at least some basic ideas in probability and statistics.

If integers in the range 1 through 10 inclusive are considered, what is the likelihood (chance, probability) that the number 5 will be selected at random? The answer is 1 in 10, or 0.1. This is true each time the question is asked. If the number 5 has just been chosen and another number is to be chosen, what is the chance that it will be a 5? Same answer: 1 in 10. The principle is that the next choice does not depend on the previous one.

Perhaps the wrong question is being asked. What is the likelihood that the number 5 will be selected twice in a row at random? The answer is 1 in 100, or 0.01. Why? Because it depends on the question asked. To get two in a row, the first one must be a 5 (1 in 10) and the second one must also be a 5 (also 1 in 10), so the resulting likelihood is 1 in 10*10 or 1 in 100. But each time a number is chosen, the number 5 has a 1 in 10 chance of being selected. A mathematical discussion of randomness depends on the asking the right question, and on probabilities. If some event is completely random, then it should have the same probability of happening as the other possible events, but events can be collected to form more complex events. Each card in a deck of playing cards should have the same probability of turning up, but if the question is "What's the chance of a flush?," then the different ways that a flush can be comprised have to be taken into account.

Numbers, in particular, are random only with respect to each other. Is the number 6 random? That's not really a good question. Is the sequence 87394 random? Perhaps a test could be devised to answer that. Is the sequence 66666 random? Most would say not, but it has the same probability of being generated at random as does 87354. To create good games and simulations, it is necessary to devise ways to generate a random number using a computer and to test numbers to see if they are in fact random. Then it would be possible to simulate the flipping of a coin or the rolling of a die.

What is the 100^{th} digit of pi? It can be found easily. Are consecutive digits of pi effectively random? As it happens, the answer is not known, but it is a good question. What is 108763 is divided by 98581? What is the remainder? Call the remainder x: what is 108763 divided by x? Are these numbers random? The search for a method for generating really good random numbers continues, but there are some pretty good methods (See Chapter 10). In Python, a random number created by a computer algorithm can be requested by using a built-in function.

A built-in function is like a mathematical function, and it is provided by the language itself. The language element **print** is a built-in function, as are **int ()** and **float ()**. The functions *sine* and *square root* are also built-in functions. Such functions belong to *modules* in Python and have to be requested by the program so that they can be used. This means that the name of the module has to be known as well as the names of the built-in functions within it. The common mathematical functions are located within the module **math** and can be used by requesting the math module with the statement:

```
import math
```

Using a function in the math module involves using the name math followed by a period (.) followed by the name of the function. The "." opens the module so that the names within can be used, because there may be other built-in functions or even variables that have the same name. If the statements

```
x = math.sqrt(64)
print (x)
```

are executed, the program prints the number 8, which is the square root of 64. The expression **sqrt (64)** is called a *function call*, and executes the code needed to calculate the square root of 64. The name **sqrt** is the name of the function, which is code provided by the Python language. This particular call always returns the value 8, because 8 is always the square root of 64. A module can be thought of as a bag of programs. Each bag contains a set of programs that do a particular class of things, like mathematics or drawing. By specifying the name of the module, access to all of the functions within is granted, and by specifying the specific name of a function, the code that we want is specifically made available.

The **import** statement should be at the very beginning of the program.

Imagine that it is possible to have a function that produces a random number as a value. It is in the module named **random**, and the function is called **random,** too. For example,

```
import random
print ( random.random() )
```

Every time the function is used, it gives a different value, a random value. This value can be used to make games more realistic, because games have a random aspect.

This code prints the value 0.07229650795715237. Why? Because **random.random ()** produces a random number between 0.0 and 1.0. This is the most common example of a random number function, and is really very general. Increasing the range is done simply by multiplying by the maximum value desired; **random.random ()*100** gives a random number between 0 and 100, for instance.

What if the problem is to simulate the roll of a die? The bag of code that is the **random** module contains other functions related to the generation of random numbers, and one of them is especially suited to this problem. A die roll would be implemented as follows:

```
random.randint (1, 6)
```

The **randint** function accepts two numbers, called *parameters*. The first is the lower limit of the range of random integers to be produced and the second is the upper limit. Specifying 1 as the lower limit and 6 as the upper limit, as in the example above, means that it will generate numbers between 1 and 6 inclusive, which is what would be expected from rolling a die. The result of rolling two dice would be a number between 2 and 12, found by **random.randint (2,12)**.

Flipping a coin is a two-level choice, and could be done with **random.randint (1,2)**.

```
if (random.randint(1,2) == 1):
    print ("Heads")
else:
    print ("Tails")
```

Going back again to the number guessing game, a random choice for the computer's number is now possible. Instead of the first line of code being

```
choice = 7
```

it should now be

```
choice = random.randint(1,10)
```

Every time the program executes the program, it will select a new random number, as opposed to the choice always being 7.

The introduction of a random choice is a little more complicated for the rock-paper-scissors program because the variable holding the player's choice is a string. There are three possible choices, so to select one at random might look like this:

```
i = random.randint(1,3)
if i == 1:
    choice = "rock"
elif i == 2:
    choice = "paper"
else:
    choice = "scissors"
```

Many of the examples in this book involve a game or puzzle of some kind, so the use of random numbers will be a consistent feature of the code shown.

2.3 COUNTING LOOPS

Features of programming languages are provided because the designers know they are useful. The **while** loop is obviously useful, and is the only kind of loop required to implement a program. However, loops that involve counting a certain number of iterations are common, and adding syntax is valuable. Sometimes a loop that executes, for example, ten times, or a loop that iterates N times for some variable N, is needed. In Python, this is called a **for** loop.

In some languages, a **for** loop involves a special syntax, but in Python, it involves a new type (a class of types, really): a *tuple*. Here is an example of a **for** loop:

```
for i in (1,2,3,4,5):
    print i
```

This code prints the numbers 1 2 3 4 5 each on a separate line. The variable **i** takes on each of the values in the collection provided in parentheses and the loop executes once for each value of **i**. The collection (1,2,3,4,5) is called a *tuple*, and can contain any Python objects in any order. It's basically just a set of objects. The following are legal *tuples*:

```
(3,6, 9, 12)
(2.1, 3.5, 9.1, 0, 12)
("green", "yellow", "red")
("red", 3, 4.5, 2, "blue", i) #where i is a variable
                                with a value
```

The **for** loop has the loop control variable (in the case above it is **i**) take on each of the values in the tuple, in left to right order, then executes the connected suite. The loop therefore executes the same number of times as there are elements in the tuple.

Sometimes it may be necessary to have the loop execute a great many times. If the loop was to execute a million times, it would be difficult to require a program to list a million integers in a tuple. Python provides a function to make this more convenient: **range()**. It returns a tuple that consists of all of the integers between the two parameters it is given, including the lower end point.

```
range (1,10)   is (1,2,3,4,5,6,7,8,9)
range (-1, 2) is (-1, 0, 1)
range (-1, -3) is not a proper range.
range (1, 1000000) if the set of all integers
                   from 1 to 9999999
```

Ranges involving strings are not allowed, although tuples with strings in them are allowed. The original example for loop can now be written:

```
for i in range(1,6):
    print i
```

and the loop that is to execute a million times could be specified as

```
for i in (0, 1000000):
    print i
```

This code prints the integers from 0 to 999999. If **range()** is passed only a single argument, then the range is assumed to start at 0; this means that **range (0,10)** and **range (10)** are the same.

2.4 PRIME OR NON-PRIME

Here's a game that can illustrate the use of a **for** loop, and some other ideas as well. The computer presents the player with large numbers, one at a time. The player has to guess whether each number is *prime* or *non-prime*. A prime number does not have any divisors except 1 and

for	i	in	2,7,8	:
The key word, known by Python, that indicates that this is a **for** statement.	A variable, the loop control variable, that will take on values in a given sequence	The key word **in**, which is basically a placeholder	A tuple (or other sequence type) that enumerates the values the variable will take	The colon indicates the end of the first part of the statement. Think of it as meaning **do**, as in **for i in (2,7,8) do**

Figure 2.2
The structure of a FOR statement

itself. 3, 5, 11, and 17 are prime numbers. The game ends either when a specific number of guesses have been made, or when the player makes a specific number of mistakes.

A key problem to solve in this game is to determine when a number is prime. The computer must be able to determine whether the player is correct, and so for any given number there must be a way to figure out whether it is prime. Otherwise, the program for this game is not complicated:

```
while game is not over:
    select a random integer k
    print k and ask the player if it is prime
    read the player's answer
    if player's answer is correct:
        print "You are right"
    else:
        print "You are wrong."
```

The mysterious portion of this program is the **if** statement that asks if the player's answer is correct. This means that the program must determine whether the number K is prime and then see if the player agrees. How can it be determined that a number is prime? A prime number has no divisors, so if one can be found, then the number is not prime. The *modulo* operator **%** can be used to tell if a division has a remainder: if k % n = 0, then the number n divides evenly into k, and k is not prime.

To find out whether a number is prime, try dividing it by all numbers smaller than it and if any of them have a zero remainder, then the number is not prime. We need to use a **for** loop.

```
isprime = True
for n in range (1, K):
    if k%n == 0:
        isprime = False
```

After the loop has completed, the variable **isprime** indicates whether K is prime. This seems simple, if tedious. It does perform a lot of divisions. Too many, in fact, because it is not possible for any number larger than K/2 to divide evenly into K. A slightly better program is as follows:

```
isprime = True               # Is the number K prime?
for n in range (1, int(k/2)) # Divide K by all numbers < K/2
    if k%n == 0:             # If the remainder is 0 then n
        isprime = False      # divides evenly into K: not
                             # prime
# If isprime is still true here, then the number is prime.
```

Next, this section of program should be incorporated into a complete program that plays the game. If the game is supposed to allow 10 guesses, then the first step is to repeat the whole thing 10 times:

```
import random
correct = 0               # The number of correct guesses
for iteration in range(0, 10):  # 10 guesses
```

Now, select a number at random. It should be large enough so that it is hard to see immediately if it is prime, although even numbers are a giveaway:

```
K = random.randint(10000, 1000000)  # Generate a new number
```

Next, print a message to the user asking for their guess, and read it:

```
print ("Prime or Not: Is the number ",K," prime? (yes or
        no)")
answer = input()      # Read the user's choice
```

The user types in a string, "yes" or "no," as their response. The variable **isprime** was used in the program that determines whether K is prime is logical, being **True** or **False**. It could be made into a string, so that it is the same as what the user typed, and then it could be compared directly against the user's input:

```
isprime = "yes"
```

Now comes the code for determining primality as coded above, except with **isprime** as a string:

```
isprime = True               # Is the number K prime?
for n in range (1, int(k/2)) # Divide K by all numbers < K/2
    if k%n == 0:             # If the remainder is 0 then n
        isprime = "no"       # divides evenly into K: not
                             # prime
# If isprime is still true here then the number is prime.
```

At this point the variable **isprime** is either "yes" or "no," depending on whether K is actually prime. The user's guess is also "yes" or "no." If they are equal, then the user guessed correctly.

```
if isprime==answer:
    print ("You are correct!")
    correct = correct + 1
else:
    print ("You are incorrect.")
```

Finally, the outer loop ends, and the result is printed. The value of the variable **correct** is the number of correct guesses the user made, because it was incremented every time a correct answer was detected. The last statement is

```
print ("You gave ",correct," right answers out of 10.")
```

ON THE CD

This program can be found on the CD in the directory “primegame.”

2.4.1 Exiting from a Loop

A clever programmer would notice a serious inefficiency with the prime number program. When it has been determined that the number is not prime, the loop continues to divide more numbers into **k** until **k/2** of them have been tried. If k= 999992, then it is known after the first iteration that the number if not prime; it is even, so can’t be prime. But the program continues to try nearly another half million numbers anyway. What is needed is a way to tell the program that the loop is over. There is a way to do this.

A loop can be exited using the **break** statement. It is simply the word **break** by itself. The correct way to use this in the program above is as follows:

```
for n in range (1, int(k/2)) # Divide K by all numbers < K/2
    if k%n == 0:             # If the remainder is 0 then n
        isprime = "no"       # divides evenly into K: not
                             # prime
        break
```

This loop terminates when the number **k** is known to be not prime. The statement following the loop is executed next. This can save a lot of computer cycles, but does not make the program more correct – just faster.

A variation on this is the **continue** statement. This statement results in the next iteration of the loop being started without executing any more statements in the current iteration. This avoids doing a lot of work in a loop after it is known it’s not necessary. For example, doing some task for a list of names, except for people named “Smith,” could use a continue statement:

```
for name in ('Jones','Smith','Peters','Sinatra','Bohr',
             'Conrad'):
    print (name);
    if name == 'Smith':
        continue
# Now do a bunch of stuff …
```

Both the **break** and **continue** do the same thing in **while** and **for** loops.

Modifying the loop variable does not change the number of iterations the loop will execute. In fact, it has no effect. This loop demonstrates that:

```
for i in range(0, 10):
    print ("Before ",i)
    i = i + 1000
    print ("After ",i)
```

It prints

```
Before  0
After  1000
Before  1
After  1001
   .  .  .
```

and so on. It seems that the value of **i** changes after the assignment for the remainder of the loop and then is set to what it should be for the next iteration. This makes sense if Python is treating the range as a set of elements (it is), and it assigns the next one to **i** at the beginning of each iteration. Unlike a **while** loop, there is no test for continuation. In any case, changing **i** here does not alter the number of iterations and can't be used in place of a **break**.

2.4.2 Else

The idea that the loop can be exited explicitly makes the normal termination of the loop something that should be detectable, too. When a while or for loop exits normally by exhausting the iterations or having the expression become **False,** it is said to have *fallen through*. When the **for** loop in the prime number program detects a factor, it executes a **break** statement, thus exiting the loop. What if it never does that? In that case, no factor exists, and the number is prime. The program as it stands has a flag that indicates this, but it could be done with an **else** clause on the loop.

The **else** part of a **while** or **for** loop is executed only if the loop falls through; that is, when it is not exited through a **break**. This can be quite useful, especially when the loop is involved in a search, as will be discussed later. In the case of the prime number program, an else could be used when the number is prime, as follows:

```
for n in range (1, int(k/2))# Divide K by all numbers < K/2
    if k%n == 0:            # If the remainder is 0, then n
        isprime = "no"      # divides evenly into K: not
                            # prime
        break
else:
    isprime = "yes"         # Loop not exited: it is prime
```

An **else** in a **while** loop occurs when the condition becomes false. Consider a loop that reads from input until the user types "end" and is searching for the name "Smith:"

```
inp = input()
while (inp != "Smith"):
    s = input()
    if s == "end":
        break
else:
    print ("Smith was found")
# When the program reaches this point it is no
# longer known whether Smith was found.
```

Of course, the **else** is not required, and some programmers believe it is even harmful. There are always other ways to accomplish the same thing.

2.5 LOOPS THAT ARE NESTED

Just as it is possible to have if statements nested within other if statements, it is possible, and even likely, to have a loop nested within another loop. An example of nested **for** loops is as follows:

```
for i in range(0, 10)
    for j in range (0, 10)
        print (i,j)
```

The **print** statement in this example executes 100 times. Each time the outer loop executes once, the inner one is executed 10 times, for a total of 10 * 10 or 100 iterations. Loops can be nested to a greater depth if necessary, and **while** and **for** loops can be nested interchangeably.

Since there was a discussion of prime numbers and factoring, consider the problem of finding the number within a given range that has the greatest number of different factors. Leaving out 1 and the number itself, 2 has no factors, nor does 3; 4 has one (=2), 5 has none, and 6 has two (2 and 3). Which number between 0 and 1000 has the most?

From the prime number game, it is clear that the factors can be found using a loop. If the loop is not exited when one is found, all of them can be identified and, more importantly for this problem, counted. For a given number **k**, the factors can be identified using the following loop:

```
count = 0;
for n in range (1, int(k/2)): # Divide K by all numbers < K/2
    if k%n == 0:              # If the remainder is 0 then n
        count = count + 1
# The number k has count numbers that divide evenly into it.
```

The statement **count = count + 1** has replaced the **isprime = "no"** statement from the prime number game. When the loop ends, the value of **count** is the number of divisors it has. If this number is 0, then the number **k** is prime. The problem has been solved for any number **k**. Now solve it for all numbers between 1 and1000 and identify the number with the largest value of **count** (i.e., the largest number of divisors). This involves another loop enclosing this one that counts from 1 to 1000.

Define a variable **maxv** which is, at any given moment, the number that has the greatest number of divisors, and another variable **maxcount,** which is the number of divisors that **maxv** has. Initially **maxv** is 1 and **maxcount** is 0 (i.e., the number 1 has no divisors). Now loop between 1 and 1000 and replace **maxv** and **maxcount** whenever a new number is found for which the number of divisors is greater than **maxcount**. Specifically,

```
maxv = 1
maxcount = 0
for k in range(1, 1000):   # Count the divisors for a range
    count = 0;
    for n in range (2, int(k/2)): # Divide K by all numbers
                                  # < K/2
        if k%n == 0:              # If the remainder is 0
                                  # then n
            count = count + 1     # Count this divisor
    if count > maxcount:          # A new maximum
        maxcount = count          # Save the count
```

```
        maxv = k                  # and the value itself
print ("The most divisors is ",maxv," with ",maxcount)
```

The result for 1 to 1000 is as follows:

```
The most divisors is 840 with 30
```

The result for 1 to 10000 is as follows:

```
The most divisors is 7560 with 62
```

This last version needs 10 seconds to execute.

2.6 DRAW A HISTOGRAM

A histogram is a kind of graph. It usually represents the frequency of the occurrence of certain discrete values. Common examples include temperature as a function of the month, or histograms of income as a function of year, age, race, or gender. Drawing one involves knowing how many categories there are and what the numerical values are for each category. Then the numbers are scaled so they fit in a particular area and the rectangles are drawn so that the heights reflect the relative numerical values. Figure 2.3 shows some typical examples.

A company wishes to plot a histogram of their income for each quarter of 2016. The numerical values are stored in variables Q1, Q2, Q3, and Q4, and range between 0 and 1 million. We can draw simple histograms by using text. If the histogram is drawn so that the bars are horizontal instead of vertical, then the number of characters drawn in a row can be used to represent the "height" of the histogram bar. Using the # character, a value of 20 could be drawn as follows:

Q1: #################### 20

This is another situation where a loop is necessary.

There are three parts to the histogram bar above: the label, the bar, and the data value. The label is easy to print, and in the example there are four possibilities; these are simply printed at the beginning of each line being drawn. The data value is not necessary, but it is useful for people looking at the graph to know what the exact number is. Each # character drawn could represent a range of values. The histogram bar is the trick. If numbers up to a million must be represented, then the bar must be scaled so that it fits on a line. If 50 characters fit on a line, then each # printed needs to represent 1000000/50, or 20,000 dollars.

Another way to say this is that every $20,000 of income results in one # character being printed. How many # are printed for the first quarter? **Q1/20000** of them.

The **print** function prints out a line every time it is called. How can multiple things be printed on a line? The **print** statement has a special parameter to allow that. The call

```
print(i, end='!')
```

will print the variable **i** and then print the "!" string following that, every time. Normally, the **print** statement places an end of line character (represented as "\n") at the end of every line, but the **end=** clause allows the programmer to change this to whatever they like. If the string provided is empty (contains no characters), then nothing extra will be printed after each call, meaning specifically that no end of line will be printed. Thus, the statement

```
print ("#", end="")
```

prints one # character, but no end of line. If another # is printed, then it will come right after the one just printed. This is exactly what is needed for the histogram program. A loop that prints ten # characters on one line can now be written as:

```
for i in range(0,10):
    print ("#", end="")
```

Given that the value of the variable Q1 is between 0 and 1000000, and each 20000 should result in a single # character being printed, the first quarter histogram bar could be drawn by the following:

```
print ("Q1: ", end="")
for k in range(0, int(Q1/20000)):
    print ('#', end='')
print ("     ", q1)
```

This includes all of the labels, and the output looks like this:

Q1: ######## 190000

A complete solution to the problem would draw the histogram all four quarters, along with a heading for the graph. The output might look like this:

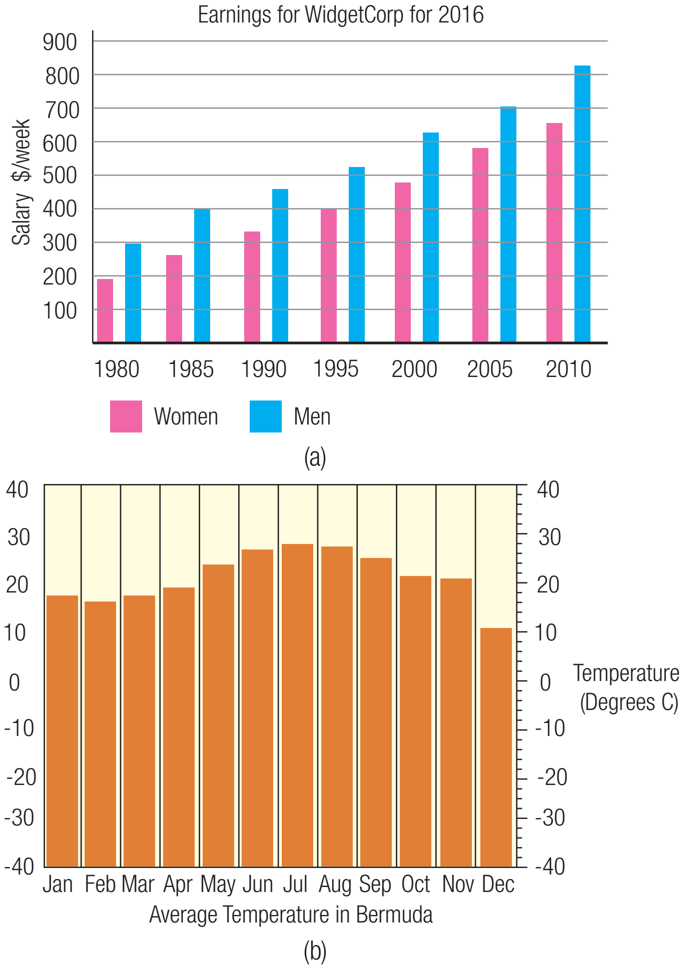


Figure 2.3
Examples of histograms.

Dollars for each quarter

==============================

Q1: ######### 190000
Q2: ################# 340000
Q3: ### 873000
Q4: ##################### 439833

Exercise 5 at the end of the chapter involves finishing this program.

2.7 LOOPS IN GENERAL

The concept of a loop in a programming language has been discussed for many years and has a large degree of both theory and practice underlying it. The original loop was a *branch* or *goto*, where the top of the loop was identified with an address or label and at the bottom there was a statement that said to "go to" or transfer control to that location. Examples of this are as follows:

```
label1:  add 1 to x                 12    x = x + 1
         subtract 2 from min              min = min - 2
         branch to label1                 go to 12
```

Branches were typical of assembly language programming, where each line of code was one actual computer instruction. The *goto* statement was introduced in the first real programming language FORTRAN, but was quickly supplemented by a more structured loop construct, the **do** statement. Both branch and goto statements can be conditional.

Various kinds of loop have been developed over the years, and the most commonly used variation is the **while** loop. Theory says that the only kind that is needed, and probably the most general, is the **loop** statement as defined in the *Ada* language. It is essentially an infinite loop that allows escapes at multiple and various points on specified conditions. The basic syntax is as follows:

```
loop
      exit when condition1;
      Statements …
      …
      exit when condition2;
end loop;
```

An **exit** at the top of the loop is a **while** loop. An exit at the end could be a **repeat** … **until** as in *Pascal* or *C++*, and it is a simple matter to declare and initialize a control variable and test the condition to implement a **for** loop. Everything is possible with this loop syntax.

When specifically using Python, a **while** loop is all that is needed. If the range is an integer one, then the loop is as follows:

```
for i in range (a .. b):
```

is the same as the loop

```
i = a
while i < b:
    …
    i= i + 1
```

This loop has an initialization, a condition, and an increment. As individual entities these are somewhat hidden in Python, being masked by the syntax, but the loop control variable takes on the first value the first time the loop is executed (initialization), iterates through the selections (increment), and terminates after it selects the final one (condition). The loop control variable is not really what gets incremented; what is incremented is a count that indicates which of the items in the tuple is currently being used. In the loop:

```
for i in ("red", "yellow", "green"):
```

the variable **i** takes on the values "red", "yellow", and "green", but what gets incremented each time through the loop is an indication of which position in the tuple is represented by **i**. The value "red" is 0, "yellow" is 1, and "green" is 2 and a count implicitly starts at 0 and steps until 2 assigning values to **i**. This kind of loop is similar to that found in the language PHP, and is a level of abstraction above those in Java and C++.

2.8 EXCEPTIONS AND ERRORS

Computers do not, as a general rule, make mistakes. Like other human-designed and constructed devices such as cars and stoves, computers can be awkward to use, can have design features that don't turn out as expected, and can even break down too quickly. But they do not make mistakes. A computer program, on the other hand, almost certainly has mistakes or *bugs* coded within it. Consumers don't usually make a distinction between the computer and the software that runs on it, but programmers and engineers must. When a computer program does not work properly, a programmer must exhaust all ways the program could be wrong before looking at an error in the computer itself.

Creating a correct program is difficult for many reasons. First, before any code is written, the problem to be solved must be clearly understood, and it must be the correct problem. Solving the wrong problem is a common error, but can't be detected or corrected by the computer. Common examples of this sort of error come from stating the problem in English (or a human language of any description) where errors in understanding occur. "Find the average of the first ten integers," for example, is a little ambiguous. Is the first integer 0 or 1? What is meant by average, the mean or the median? Computer programmers tend to be quite literal, and so what they think is the answer will be written into the code, and then they will argue for that answer as being correct. It is very important to realize that, whatever the literally correct answer is, the real correct answer is based on the correct understanding of the problem. Sometimes it is stated badly, but no matter whose fault the problem is, the job of fixing it lies with the programmer. Sometimes a little time at the beginning clarifying the question can save more time later, and sticking with an overly pedantic interpretation will cause problems in the long run.

A correct program also depends on the programmer being able to identify all possible circumstances that can occur and knowing how to deal with each of them. Failing to handle one possible situation is an error, and the program will behave unpredictably if that situation occurs in practice. Statements that handle errors appear in real (in the field or commercial) code. In fact, it is common that there are more statements that detect and deal with errors than code that actually computes an answer. One thing that should be remembered: all lines of the code need to be tested. In very large programs this may be impossible, but every line of code that has never been executed is a potential error. Test as many as possible, including the error detection code.

User input is a frequent cause of mistakes in programs. It's not that the user is the problem; the programmer must anticipate all possible ways that a user can enter data. There is usually one correct way but many erroneous ones, and it is impossible to predict what a user will enter from a keyboard in response to any request. Similarly, the contents of a file may not be what the programmer expects. File formats are standard, but sometimes there are variations and at other times a user may have entered the data improperly. While the mistake is on the part of the user, it is also a programming mistake if the error is not detected and is allowed to have an impact of the execution of the program.

Programmers tend to make assumptions about the problem. It is a common mistake to think "this situation can never happen" and then ignore it, however unlikely the situation seems. Testing every statement for everything that could possibly go wrong may be impossible, but testing for the general situation may be possible. It would be great to be able to say "if any statement in this section of code divides by zero," or "if any variables in this code have the wrong type," then do some particular thing.

Since it is impossible to write a program of any length without there being coding errors of some kind included, a step towards a solution may be to check all data before it is operated on to ensure the pending operation is going to succeed. For instance, before performing the division **a/b**, test to make sure that **b** is not zero. This depends on the error being at least in principle predictable. Most modern languages, Python included, have implemented a way to catch errors and permit the programmer to handle them without having tests before each statement or expression. This facility is called the *exception*.

The word *exception* communicates a way to think about how errors will be handled. Some code is legal and calculates a desired value *except* under certain circumstances or *unless* some particular thing happens. The way it works is that the program tries to perform some operation and errors are allowed to occur. If one does, the computer hardware or operating system detects it and tells Python. The program cannot continue in the way that was planned, which is why this is called an exception. The programmer can tell Python what to do if specific errors occur by writing some code that deals with the problem. If the programmer did not do this, then the default is for Python to print an error message that describes the error and then stop executing the program. Error messages can be seen as a failure on the part of the programmer to handle errors correctly.

A simple example is the divide by zero error mentioned previously. If the expression **a/b** is to be evaluated, the value of **b** can be checked to make sure it is not zero before the division is done:

```
if b != 0:
   c = a/b
```

This can be tedious for the programmer if a lot of calculations are being done and can be error prone. The programmer may forget to test one or two expressions, especially if engaged in modifications or testing. Using exceptions is a matter of allowing the error to happen and letting the system test for the problem. The syntax is as follows:

```
try:
      c = a/b
except:
      c = 1000000
```

The **try** statement begins a section of code within which certain errors are being handled by the programmer's code. After that statement, the code is indented to show that it is part of the **try** region. Nearly any code can appear here, but the **try** statement must be ended before the program ends.

The **except** statement consists of the key word **except** and, optionally, the name of an error. The errors are named by the Python system, and the correct name has to be used, but if no error name is given as in this example then any error will cause the code in the **except** statement to be executed. Not specifying a name here is an implicit assumption that either only one kind of error could possibly occur or that no matter what error happens, the same code will be used to deal with it. Specifying an unrecognized name is itself an error. The name can be a variable, but that variable must have been assigned a recognized error name before the error occurs. The code following the **except** keyword is indented too, to show that it is part of the **except** statement. This is referred to by programmers as an *error handler*, and is executed only if the specified error occurs.

This appears to be even more verbose than testing **b**, but any number of statements can appear between the **try** and the **except**. This section of code is now protected from divide by zero errors. If any occur, then the code following the **except** statement is executed, otherwise that code does not execute. If other errors occur, then the default action takes place – an error message is printed.

Testing specifically for the divide by zero error can be done by specifying the correct error name in the **except** statement:

```
try:
      c = a/b
except ZeroDivisionError:
      c = 1000000
```

More than one specific error can be caught in one except statement:

```
try:
      c = a/b
except (ValueError, ZeroDivisionError):
      c = 1000000
```

Clearly **(ValueError, ZeroDivisionError)** is a tuple, and could be made longer and assigned to a variable.

There can be many **except** statements associated with a single **try**:

```
try:
      c = a/b
except ValueError:
   c = 0
exceptZeroDivisionError:
      c = 1000000
```

As was mentioned earlier, a variable can hold the value of the error to be caught:

```
k = ZeroDivisionError
try:
      c = a/b
except k:
      c = 1000000
```

Finally, the exception name can be left out altogether. In that case, any exception that occurs will be caught and the exception code will be executed:

```
try:
      c = a/b
except:
   c = 0
```

2.8.1 Problem: A Final Look at Guess a Number

The final version of the program involving guessing a number looks like this:

```
choice = 7
print ("Please guess a number between 1 and 10: ")
playerchoice = int(input())
if choice == playerchoice:
    print ("You win!")
else:
    print ("Sorry, you lose.")
```

Using exceptions and what has been discussed about error checking, this program can be improved. First, if the user enters something that is not an integer, it is an error. This should be caught using an exception. Rather than forcing the player to run the program again, a loop can be used to ask for another guess. The **input** should be within the **try** statement. The **except** statement should print an error message, and the entire collection should be within a loop that continues to ask the user to guess a number. Here is a better version:

```
choice = 7
guessed = False    # Has the user guessed a reasonable num-
ber?
while not guessed: # Keep trying until they have
    print ("Please guess a number between 1 and 10: ")
    try:           # Catch potential input errors
        playerchoice = int(input())
        guessed = True  # Success so far
    except:        # An error occurred.
        print ("Sorry, your guess must be an integer.")
if choice == playerchoice:  # Correct guess?
    print ("You win!")
else:
    print ("Sorry, you lose.")
```

The variable **guessed** is set to **True** when a successful guess is made, and this stops the loop from repeating. If the user enters a real number or a string, the exception is caught before that happens, the error message is printed, and the user is asked to enter another guess.

What else is wrong with this code? The user is asked to enter a number between 1 and 10, but that value is never checked to see if it is valid. If it falls outside the range, then it will always be an incorrect guess and the player will lose. It's a penalty for not paying attention to the rules. A program should give the user as much information as is reasonable, so it would be better to check the value of the variable **playerchoice** and give an error message if it is out of range. The best way to do this is to place the check after the **except** statement at the bottom of the loop, and set the variable guessed to **False** if the guess is an improper one. Then the loop will repeat and the player will get another guess.

This version of the program is as follows:

```
choice = 7
guessed = False
while not guessed:
    print ("Please guess a number between 1 and 10: ")
    try:
        playerchoice = int(input())
        guessed = True
```

```
    except:
        print ("Sorry, your guess must be an integer.")
    if playerchoice<10 or playerchoice>10: # Is the guess
                                           # in 1..10?
        print ("Your guess was",playerchoice,
                    "which is out of range.")
       guessed = False                   # Nope. Guess again
if choice == playerchoice:
    print ("You win!")
else:
    print ("Sorry, you lose.")
```

2.9 SUMMARY

The ability to repeat a collection of operations is an essential part of any programming language. The **while** loop has a condition at the beginning, and so long as that condition is true, the statements comprising the loop will be executed repeatedly. The **for** loop has an explicit list of items for which the loop will be executed or a range of numerical values that define how many times the code will be repeated.

Most problems solved using a computer program have some degree of repetition implicit in the implementation, and some computer algorithms are quite explicit about how the iterations are to be used and how many are needed to solve the problem (See Exercises 3 and 4)

Certain errors that can occur in programs can be detected automatically by Python. If the programmer does not address these errors, they result in a message and premature program termination. The **try-except** statement allows the programmer to handle errors without ending the program, and permits better communication of the kind of error that occurred, in the context of the program, to the programmer or user.

Exercises

1. Given the following definitions

```
var1 = 12
var2 = 100
var3 = -2
var4 = 0
```

What is printed by the following **while** loops?

a.
```
while var1 < var2:
  print (var1)
  var1 = var1 + 30
```

b.
```
while var1 < var2:
    print (var1)
    var1 = var1 * 2
```

c.
```
while var1 > 0:
      var4 = var4 + 1
      var1 = var1 - 1
  print (var1, var2)
```

d.
```
while var1 > 0:
      var4 = var4 + 1
     var1 = var1 - var4
  print (var1, var2)
```

3.
```
while var1 < var3:
    print ("*", end="")
    var3 = var3 + 2
```

f.
```
while var2 > var1*var4:
      var1 = var1 + 1
      var4 = var4 + 1
  print (var1, var2)
```

2. What is printed by the following **for** loops?

a.
```
for i in range (1, 10):
      print (i)
```

b.
```
for i in (1, 10):
      print (i)
```

c.
```
for i in ("red", "green", "blue"):
      print (i)
```

d.
```
for i in range(0, 10):
```

```
        for j in range(1, 10):
            if i == j:
               print (i)
```

e.
```
for i in range(0, 10):
       for j in range(0, 50):
           if i*i == j:
              print (i)
```

d.
```
for i in (0, 10):
    i = i * 2
    print (i)
```

e.
```
for i in range (1, 10):
    for j in range (1, i):
        print (j, end="")
    print()
```

f.
```
for i in range(0, 10):
    i = i + 1
    for j in range (1, i):
        print (j, end="")
   print()
```

3. The Greek mathematician Zeno (c. 450 BCE) is credited with creating the paradox of the Tortoise and Achilles. A tortoise challenged the great hero and athlete Achilles to a footrace. All the tortoise asked was a ten-yard head start. The idea was that once the race began, Achilles could run the ten-yard head start in a small time; however, in that same time, the tortoise would move forward a small amount, perhaps a yard. When Achilles made up that yard, the tortoise would have moved ahead again a small distance; and so on. The logic was that Achilles could never catch up. The misunderstanding here is that an infinitely long series of numbers can add up to a finite value. Write a small Python program that sums the numbers ½, ¼, $^1/_8$, $^1/_{16}$, and so on for 20 iterations and suggest what the sum would be if it were carried to an infinite number of iterations.

4. One way to calculate the square root of a number is to use *Newton's method*. This starts with an initial guess: if the square root of **x** is being computed, then a fair initial guess **g** would be **x/2**. Successive estimates are given by the expression:

```
newg = (g + x/g)/2
```

Successive estimates are nearer to the actual square root. Write a program to computer the square root of a number that is entered from the keyboard.

5. Complete the program that draws a histogram for the earnings of WidgetCorp for four quarters of 2016. Earnings are as follows:
   a. 190000
   b. 340000
   c. 873000
   d. 439833

6. Modify the program in Exercise 5 above so that the data for the four quarters is read from the terminal (i.e., entered by the user from the keyboard). Test it for the following values:
   a. 900000
   b. 874000
   c. 200000
   d. 439000

7. Modify the solution to Exercise 6 in Chapter 1 (making change) so that it makes effective use of a **for** loop. The program should still read a number between 1 and 99, which is an amount of change to be given, and print the coin values that would be used. Modify it to not use a half-dollar coin, because nobody has those anymore.

8. Convert the following **for** loops into the equivalent **while** loop:

   a.
   ```
   for i in range (1, 10):
       print (i, i*i)
   ```

   b.
   ```
   sum = 0
   for i in (range (10, 0, -1):
       sum = sum + i
       print (i, sum)
   ```

9. A good solution to Exercise 4 above (square root) would detect negative numbers and print a message to the effect that square roots of negative numbers do not exist (not as real numbers, anyway). Modify the solution to Exercise 4 to use an exception to deal with that situation, and handle other potential errors.

Notes and Other Resources

Online tutorial on Python loops: *http://www.tutorialspoint.com/python/python_loops.htm*

Cornell University summary of **if** statements and loops: *http://www.cs.cornell.edu/courses/cs1130/2012sp/1130selfpaced/module2/module2part1/ifloop.html*

Sthurlow.com: *http://sthurlow.com/python/lesson04/*

1. Henry Ford and Samuel Crowther (1922). *My Life and Work,* Garden City Publishing, Garden City, N.Y. *http://www.gutenberg.org/ebooks/7213*
2. David Beazley and Brian K. Jones, *Python Cookbook*, *3rd Edition: Recipes for Mastering Python 3*, *http://www.onlineprogrammingbooks.com/python-cookbook-third-edition/*

CHAPTER 3

SEQUENCES: STRINGS, TUPLES, AND LISTS

In this chapter

In Chapter 2, we noted that **for** loops in Python are different from those found in many other languages. In Java and C++, a **for** loop has a very explicit increment; a **for** statement looks like this in Java:

```
for (i=0; i<10; i=i+1)
```

From this, it can be inferred that the variable **i** starts out as 0, and so long as **i** is less than 10, the loop continues. After each iteration, the value of **i** is increased by 1, and then the condition is tested again.

In Python, the iteration is more implicit, with the loop control variable taking on one of a set of values in turn. There is an implication here, too, that there is a kind of thing, a type that a variable can have, that amounts to a list or sequence of other, simpler things. This is true, and using variables having these types are an essential part of writing useful and effective code. Python offers strings, tuples, and lists as objects that consist of multiple parts. They are called sequence types. An integer or a float is a single number, whereas a sequence type consists of a collection of items, each of which is a number or a character. Each member of a sequence is given a number based on its position: the first element in the sequence is given 0, the second is 1, and so on. This is a fundamental data structure in Python and has influenced the syntax of the language.

Strings are familiar objects and have been used in programs already, so our discussion begins there.

3.1 STRINGS

A *string* is a sequence of characters. The word *sequence* implies that the order of the characters within the string matters, and that is certainly true. Strings most often represent the way that communication between a computer and a human takes place. Human language consists of words and phrases, and each word or phrase is a string within a program. The order of the characters within a word matters a great deal to a human because some sequences are words and others are not. The string “last” is a word, but “astl” is not. The strings “salt” and “slat” are words and use exactly the same characters as “last,” but these characters are arranged in a different order.

Because order matters, the representation of a string on a computer imposes an order on the characters within, and so there is a first character, a second, and so on, and it should be possible to access each character individually. A string also has a *length*, which is the number of characters within it. A computer language provides specific actions that can be done to a string: these are called *operations*, and a type is defined at least partly by what operations can be done to something of that type. Because a string represents text in the human sense, the operations on strings should represent the kinds of things that would be done to text. This includes printing and reading, accessing any character, linking strings into longer strings, and searching a string for a particular word.

The examples of code written so far use only string *constants*. These are simply characters enclosed in either single or double quotes. Assigning a string constant to a variable causes that variable to have the string type and gives it a value. The statements

```
name = "John Doe"
address = '121 Second Street'
```

cause the variables named **name** and **address** to be strings with the assigned value. Note that either type of quote can be used, but a string that begins with a double quote must end with one.

A string behaves as if its characters are stored as consecutive characters in memory. The first character in a string is at location or index 0, and can be accessed using square brackets after the string name. Using the definitions above, name[0] is "J" and name[5] = "D." If an index is specified that is too large, it results in an error because it amounts to an attempt to look past the end of the string.

How many characters are there in the string **name**? The built-in function **len()** returns the length of the string. The largest legal index is one less than this value: the first character of a string **name** has index 0, and the final one has index 7; the length is 8. Thus, any index between 0 and **len(name)-1** is legal. The following code prints all of the characters of **name** and can be thought of as the basic pattern for code that scans through the characters in strings:

```
for i in range(0, len(name)):
    print (name[i], end="")
```

This may be a little confusing, but remember that the **range(0,n)** does not include **n**. This loop runs through values of **i** from 0 to **len(name)-1**.

Some languages have a *character* type, but Python does not. A string of length one is what Python uses instead. A component of a string is therefore another string. The first character of the string **name**, which is **name[0]**, is "J," the string containing only one character.

3.1.1 Comparing Strings

Two strings can be compared in the same manner as are two integers or real numbers, by using one of the relational operators ==, !=, <, >, <=, or >=. What it means for two strings to be equal is simple and reasonable: if each corresponding character in two strings is the same, then the strings are equal. That is, for strings **a** and **b**, if **a[0] == b[0]**, and **a[1]==b[1],** and so on to the final character **n**, and **a[n] == b[n]**, then the two strings **a** and **b** are equal and **a==b**. Otherwise **a!=b**. By the way, this implies that equal strings have the same length.

What about inequalities? Strings in real life are often sorted in alphabetical order. Names in a telephone book, files in a doctor's office, and books in a store tend to appear in a logical order based on the alphabet. This is also true in Python. The string "abc" is less than the string "def," for example. Why? Because the first letter in "abc" comes before the first letter in "def;" in other words, "abc"[0] < "def"[0]. Yes, characters in string constants can be accessed using their index.

A string **s1** is less than string **s2** and all characters from 0 through **k** in the two strings are equal, so **s1[k+1]<s2[k+1]**. Therefore, the following statements are true:

```
"abcd" < "abce"
"123" < "345"
"ab " < "abc"
```

In the last example, the space character `" "` is smaller than (i.e., comes before) the letter "c." What if the strings are not the same length? The string `"ab" < "abc"`, so if two strings are equal to the end of one of them, then the shorter one is considered to be smaller. These rules are consistent so far with those taught in grade school for alphabetization. Trailing spaces do not matter. Leading spaces can matter, because a space comes before any alphabetic character; that is, `" " < "a."` Thus `"ab" > " z."`

Digits come before lowercase letters. `"1" < "a,"` and `"1a" < "a1."` Most importantly, uppercase letters come before lowercase letters, so `"John" < "john."` All of these rules are consistent with those that secretaries understand when filing paper documents. As an example that compares strings, consider the following:

```
a = "J"
b = "j"
c = "1"
if b<c:
    print ("Lcase < numbers")
else:
    print("Lcase > numbers")
if a<c:
    print ("Ucase < numbers")
else:
    print("Ucase > numbers")
```

This results in the following output:

```
Lcase > numbers
Ucase > numbers
```

Problem: Does a city name, entered at the console, come before or after the name *Denver*?

This involves reading a string and comparing it against the constant string "Denver." Let the input string be read into a variable named **city**. Then the answer is as follows:

```
city = input()
if city < "Denver":
    print ("The name given comes before Denver in an
            alphabetic list")
elif city > "Denver":
    print ("The name given comes after Denver in an
            alphabetic list")
else:
    print ("The name given was Denver")
```

If "Chicago" is typed at the console as input, the result is as follows:

```
Chicago

The name given comes before Denver in an alphabetic list
```

However, if case is ignored and "chicago" is typed instead, then the result is as follows:

```
chicago
The name given comes after Denver in an alphabetic list
```

because, of course, the lower case "c" comes (as do *all* lowercase letters) after the uppercase "D" at the beginning of "Denver."

3.1.2 Slicing – Extracting Parts of Strings

To a person, a string usually contains words and phrases, which are smaller parts of a string. Identifying individual words is important. To Python, this is true also. A Python program consists of statements that contain individual words and character sequences that each have a particular meaning. The words "if," "while," and "for" are good examples. Individual characters can be referenced through indexing, but can words or collections of characters be accessed? Yes, they can be accessed if the location (index) or the word is known.

Problem: Identify a "print" statement in a string.

The statement

```
print ("Lcase < numbers")
```

appears in the example program above. This can be thought of as a string and assigned to a variable:

```
statement = 'print ("Lcase < numbers")'
```

Is this a **print** statement? It is if the first five characters are the word "print." Each of those characters could be tested individually using the following code:

```
if statement[0] == 'p':
    if statement[1] == 'r':
        if statement[2] == 'i':
            if statement[3]=='n':
                if statement[4]=='t':
                   if statement[5]==' ':
                       # This is a print statement.
```

This is not an attractive format, and since this is something that is needed often enough, Python offers a better way to write it. A *slice* is a set of continuous characters within a string. This means their indices are consecutive, and they can be access as a sequence by specifying the range of indices within brackets. The situation above concerning the print statement could be written like this:

```
if statement[0:5] == "print":
```

The slice here does not include character 5, but is 5 characters long, including the characters 0 through 4, inclusive. A slice from **i** to **j** (i.e., **x[i:j]**) does not include character **j**. This means that the following statements produce the same result:

```
fname[0]
fname[0:1]
```

If the first index is omitted, then the start index is assumed, so the statement

```
if statement[0:5] == "print":
```

is the same as

```
if statement[:5] == "print":
```

If the second index is omitted, then the last legal index is assumed, which is to say the index of the final character. The assignment

```
    str = statement[6:]
```

results in the value of **str** being (**"Lcase < numbers"**). Both indices can be omitted, which means we use everything from the first to the last character, or the entire string.

3.1.3 Editing Strings

Python does not allow the modification of individual parts of a string. That is, statements like

```
str[3] = "#"
str[2:3] = ".."
```

are not allowed. How can strings be modified? For example, consider the string variable

```
fname = "image"
```

If this is supposed to be the name of a JPG image file, then it must end with the suffix ".jpg."

Problem: Create a JPEG file name from a basic string

The string **fname** can be edited to end with ".jpg" in a few ways, but the easiest one to use is the concatenation operator, +.

To *concatenate* means "to link or join together." If the variables **a** and **b** are strings, then **a+b** is the string consisting of all characters in **a** followed by all characters in **b**; the operator + in this context means to concatenate, rather than to add numerically. The designers of Python and many other languages that implement this operator think of concatenation as string addition.

To use this to create the image file name, simply concatenate ".jpg" to the string **fname**:

```
fname = fname + ".jpg"
```

The result is that **fname** contains "image.jpg."

File suffixes are very often the subject of string manipulations and provide a good example of string editing. For instance, given a file name stored as a string variable **fname**, is the suffix .jpg? Based on the preceding discussion, the question can be answered using a simple **if** statement:

```
if fname[len(fname)-4:len(fname)] == '.jpg':
```

Using a slice, it could also take the form

```
if fname[len(fname)-4:] == ".jpg"
```

A valuable thing to know is that negative indices index from the right side of the string, that is, from the end. Therefore, **fname[-1]** is the final character in the string, **fname[-2]** is the one previous to that, and so on. The last 4 characters, the suffix, are captured by using **filename[-4:]**.

Problem: Change the suffix of a file name

Some individuals use the suffix .jpeg instead of .jpg. Some programs allow this, others do not. Some code that would detect and change this suffix is as follows:

```
if fname[len(fname)-5:] == ".jpeg":  # identfy the jpeg
                                      # suffix
    fname = fname[0:len(fname)-5]     # remove the last five
                                      # characters
    fname = fname + ".jpg"            # append the correct
                                      # suffix
```

Problem: Reverse the order of characters in a string

There are things about any programming language that could be considered idioms. These are things that a programmer experienced in the use of that language would consider normal use, but that others might consider odd. This problem exposes a Python idiom. Given what is known so far about Python, the logical approach to string reversal might be as follows:

```
# city has a legal value at this point
k = len(city)
for i in range(0,len(city)):
    city = city + city[k-i-1]
city = city[len(city)//2:]
```

This reverses the string named **city** that exists prior to the loop and creates the reversed string. It does so in the following way:

1. Let **i** be an index into the string **city**, starting at 0 and running to the final character.
2. Index a character from the end of the string, starting at the final character and stepping backwards to 0. Since the last character is len(city) and the current index is **i**, the character to be used in the current iteration would be **k-i-1,** where k is the length of the original string.
3. Append **city[k-i-1]** to the end of the string. Alternatively, a new string **rs** could be created and this character appended to it during each iteration.
4. After all the characters have been examined, the string **city** contains the original string at the beginning and the reversed string at the end. The first characters can be removed, leaving the reversed string only.

An experienced Python programmer would do this differently. The syntax for taking a slice has a variation that has not been discussed; a third parameter exists. A string slice can be expressed as

```
myString[a:b:c]
```

where **a** is the starting index, **b** is the final index+1, and **c** is the increment. If

```
str = "This string has 30 characters."
```

then str[0:30:2] is "Ti tighs3 hrces," which is every second character. The increment represents the way the string is sampled, that is, every increment's characters is copied into the result. Most relevant to the current example, the increment can be negative. The idiom for reversing a string is as follows:

```
print (str[::-1])
```

As has been explained, the value of str[:] is the whole string. Specifying an increment of -1 implies that the string is scanned from 0 to the end, but in reverse order. This is far from intuitive, but is probably the way that an experienced Python programmer would reverse a string. Any programmer should use the parts of any language that they comprehend very well, and should keep in mind the likely skill set of the people likely to read the code.

Problem: Is a given file name that of a Python program?

A Python program terminates with the suffix .py. An obvious solution to this problem is to simply look at the last 3 characters in the string **s** to see if they match that suffix:

```
if  s[len(s)-3:len(s)] == '.py':
      print ("This is a Python program.")
```

But is PROGRAM.PY a legal Python program? It happens that it is, and so is program.Py and program.pY. What can be done here?

3.1.4 String Methods

A good way to do the test in this case is to convert the suffix to all uppercase or all lowercase letters before doing the comparison. Comparing the name against .py means it should be converted to lowercase, which is done by using a built-in method named **lower**:

```
s1 = s[len(s)-3:len(s)]
if  s1.lower()== '.py':
    print ("This is a Python program.")
```

The variable **s1** is a string that contains the final 3 characters of **s**. The expression **s1.lower()** creates a copy of **s1** in which all characters are lowercase. It's called a method to distinguish it from a function, but they are very similar things. You should recall that a method is simply a function that belongs to one type or class of objects. In this case, **lower**() belongs to the type (or class) *string*. There could be another method named **lower**() that belongs to another class and that did a completely different action. The dot notation indicates that it is a method, and what class it belongs to: the same class of things that the variable belongs to. In addition, the variable itself is really the first parameter; if **lower** were a function, then it might be called by **lower(s1)** instead of **s1.lower()**. In the latter case, the "." is preceded by the first parameter.

Strings all have many methods. In Table 3.1, the variable **s** is the *target* string, the one being operated upon. This means that the method names below appear following s., as in **s.lower()**. Let the value of **s** be given by **s = "hello to you all."** These methods are intended to provide the operations needed to make the string type in Python function as a major communication device from humans to a program.

Table 3.1
String Methods and their explanations

Method	Explanation (What is returned?)	Example
`capitalize()`	Returns the target string but with the first letter capitalized.	`s.capitalize() == "Hello to you all."`
`count(str,beg=0, end=len(s))`	Returns a count of how many times the string **str** occurs in the target. If values for **beg** and **end** are given, then the count is performed using only character indices between **beg** and **end**.	`s.count("ll") == 2`
`endswith(suffix, beg=0, end=len(s))`	Returns **True** if the target string ends with the given suffix and return **False** otherwise. If **beg** and **end** are given, then do the test on the substring between **beg** and **end**.	`s.endswith('ll.') ==True`
`find(str, beg=0end=len(string))`	If the string **str** appears with the target string, then return the index at which it occurs; return -1 if it does not occur. If **beg** and **end** are provided, then use the substring from **beg** to **end**.	`s.find("you") == 9`
`index(str,beg=0, end=len(string))`	**Index** is the same as **find** except that it will raise an exception if the string **str** does nor occur in the target	`s.index("you") == 9`
`isdigit()`	Returns **True** if the target string contains only digits and **False** otherwise.	`s.isdigit() == False`
`islower()`	Returns **True** if the target string has at least 1 alphabetic character and all alphabetic characters are lowercase. Returns **False** otherwise.	`s.islower() == True`

(continued)

Method	Explanation (What is returned?)	Example
`isspace()`	Returns **True** if the target string contains only whitespace characters and returns **False** otherwise.	`s.isspace() == False`
`isupper()`	Returns True if s has at least one alphabetic character and all alphabetic characters are uppercase. Returns **False** otherwise.	`s.isupper() == False`
`lower()`	Converts all uppercase letters in string to lowercase.	`s.lower() == s`
`replace(old, new [, max])`	Replaces all occurrences of the string **old** in the target with the string **new**. If **max** is specified, replace at most **max** instances.	`s.replace("you all", "y'all") == "hello to y'all."`
`split(str="", num=string.count(str))`	Returns a list of substrings obtained from the target using **str** as a delimiter. Space is the default for str. Subdivide at most num times if that is specified (*see*: Chapter 3, section 3).	`s.split(" ") == ["hello","to", "you","all"]`
`splitlines( num=string.count('\n'))`	Splits the target string at all (or **num**, if it is specified) NEW-LINEs and returns a list of each line with the NEWLINEs removed.	`s.splitlines() == "hello to you all."`
`upper()`	Converts the lowercase letters in string to uppercase.	`s.upper() == "HELLO TO YOU ALL."`

3.1.5 Spanning Multiple Lines

Text as seen in human documents may contain many characters, even multiple lines and paragraphs. A special delimiter, the *triple quote*, is used when a string constant is to span many lines. This has been mentioned previously in the context of multi-line comments. The regular string delimiters will terminate the string at the end of the line. The triple quote consists of either of the two existing delimiters repeated three times. For example, to assign the first stanza of Byron's poem "She Walks in Beauty" to the string variable **poem**, we would write the following code:

```
poem = '''She walks in beauty like the night
Of cloudless climes and starry skies,
And all that's best of dark and bright
Meets in her aspect and her eyes;
Thus mellow'd to that tender light
Which Heaven to gaudy day denies.'''
```

When **poem** is printed, the line endings appear where they were placed in the constant. This example is a particularly good one in that most poems require that lines end precisely where the poet intended.

Another example of a string that must be presented just as typed is a Python program. A program can be placed in a string variable using a triple quote:

```
program = """list = [1,2,4,7,12,15,21]
for i in list:
    print(i, i*2)"""
```

When printed, this string has the correct form to be executed by Python. In fact, the following statement executes the code in the string:

```
exec (program)
```

3.1.6 For Loops Again

Earlier in this section, a **for** loop was written to print each character in the string. That loop was as follows:

```
for i in range(0, len(name)):
    print (name[i], end="")
```

Obviously, the string could have been printed using

```
print(name)
```

but it was being used as an example of indexing individual components within the string. The characters do not need to be indexed explicitly in Python; the loop variable can be assigned the value of each component:

```
for i in name:
    print (i, end="")
```

In this case, the value of **i** is the value of the component, not its index. Each component of the string is assigned to **i** in turn, and there is no need to test for the end of the string or to know its length. This is a better way to access components in a string and can be used with all sequence types. Whether an index is used or the components are pulled out one at a time depends on the problem being solved; sometimes the index is needed, other times it is not.

3.2 THE TYPE *BYTES*

A string is a sequence of characters, a sequence being defined as a collection within which order matters. Strings are commonly used for communication between computers and humans: to print headings and values on the screen, and to read objects in character string form. Humans deal with characters very well. The type *bytes* represents a sequence of integers, albeit small ones. A bytes object of length 1 is an 8-bit integer, or a value between 0 and 255. A bytes object of length greater than 1 is a sequence of small integers. To be clear, if **s** is a string and **b** is a bytes object, then

s[i] is a character
b[i] is a small integer

A string constant (literal) is a sequence of characters enclosed in quotes. A bytes literal is a sequence of character enclosed in quotes and preceded by the letter "b." Thus

```
'this is a string'
```

is a string, whereas

```
b'this is a string'
```

has type bytes. Any method that applies to a string also applies to a bytes object, but bytes objects have some new ones. In particular, to convert a bytes object to a string, the **decode()** method is used, and a character encoding should be given as the parameter. If no parameter is given, then the decoding method is the one currently being used. There are a few possible decoding methods (e.g., utf-8). To convert a bytes object **b** to a character string **s**, the following would work:

```
s = b.decode ("utf-8")
```

A question remains: why is the bytes type needed? The bytes type implements the *buffer interface*. Certain file operations require a buffer interface to accomplish their tasks. Anything read from some specific types of files will be of the type bytes, for example, as it has that interface. This will be discussed further in Chapters 5 and 8. Other than the buffer interface, the bytes type is very much like a string, and can be converted back and forth.

3.3 TUPLES

A *tuple* is almost identical to a string in basic structure, except that it is composed of arbitrary components instead of characters. The quotes cannot be used to delimit a tuple because a string can be a component, so a tuple is generally enclosed in parentheses. The following are tuples:

```
tup1 = (2, 3, 5, 7, 11, 13, 17, 19)  # Prime numbers under 20
tup2 = ("Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon")
tup3 = "hi", "ohio", "salut"
```

If there is only one element in a tuple, there should be a comma at the end:

```
tup4 = ("one",)
tup5 = "two",
```

That's because it would not be possible otherwise to tell the difference between a tuple and a string enclosed in parentheses. Is (1) a tuple? Or is it simply the number 1?

A tuple can be empty:

```
tup = ()
```

Because they are like strings, each element in a tuple has an index, and they begin at 0. Tuples can be indexed and sliced, just like strings.

```
tup1[2:4] is (5, 7)
```

Concatenation is like that of strings, too:

```
tup4 = tup4 + tup5          # yields tup4 = ('one', 'two')
```

As is the case with strings, the index -1 gives the last value in the tuple, -2 gives the second last, and so on. In the example above, **tup2[-1]** is "Carbon." Also, like strings, the tuple type is immutable; this means that elements in the tuple cannot be altered. Thus, statements such as

```
tup1[2] = 6
tup3[1:] "bonjour"
```

are not allowed and will generate an error.

Tuples are an intermediate form between strings and lists. They are simpler to implement than *list* (which is *lightweight*) and are more general than strings.

Are tuples useful? Yes, it turns out, and part of their use is that they underlie other aspects of Python.

3.3.1 Tuples in For Loops

Sequences can be used in a **for** loop to control the iteration and assign the loop control variable. Tuples are interesting in this context because they can consist of strings, integers, or floats. The loop

```
for i in ("Hydrogen","Helium","Lithium","Beryllium",
          "Boron","Carbon"):
```

will iterate 6 times, and the variable **i** takes on the values in the tuple in the order specified. The variable **i** is a string in this case. In cases where the types in the tuple are mixed, the situation becomes more complicated.

Problem: Print the number of neutrons in an atomic nucleus.

Consider the tuple:

```
atoms=("Hydrogen",1,"Helium",2,"Lithium",3,"Beryllium",4,
       "Boron",5,"Carbon",6)
```

and the loop

```
for i in atoms:
    print (i)
```

This prints the following:

```
Hydrogen
1
Helium
2
Lithium
3
Beryllium
4
```

```
Boron
5
Carbon
6
```

The number following the name of the element is the atomic number of that element, the number of protons in the nucleus. In this case, the type of the variable **i** alternates between string and integer. For elements with a low atomic number (less than 21), a good guess for the number of neutrons in the nucleus is twice the number of protons. The problem is that some of the components are strings and some are integers. The program should only do the calculation when it is in an iteration having an integer value for the loop variable, because a string cannot be multiplied by two.

A built-in function that can be of assistance is **isinstance**. It takes a variable and a type name and returns **True** if the variable is of that type and **False** otherwise. Using this function, here is a program that makes the neutron guess:

```
atoms=("Hydrogen",1,"Helium",2,"Lithium",3,"Beryllium",4,"B
oron",5,"Carbon",6)
for i in atoms:
    if isinstance(i, int):
        j = i*2
        print ("has ", i, "protons and ", j, " neutrons.")
    else:
        print ("Element ", i)
```

In other words, in iterations where **i** is an integer as determined by **isinstance**, then **i** can legally be multiplied by 2 and the guess about the number of neutrons can be printed.

Another way to solve the same problem is to index the elements of the tuple. Elements 0, 2, and 4 (even indices) refer to element names, while the others refer to atomic numbers. This code is as follows:

```
atoms=("Hydrogen",1,"Helium",2,"Lithium",3,"Beryllium",4,
       "Boron",5,"Carbon",6)
for i in range(0,len(atoms)):
    if i%2 == 1:
        j = atoms[i]*2
        print ("has ", atoms[i], "protons and ", j,
               " neutrons.")
    else:
        print ("Element ", atoms[i])
```

Note that in this case, the loop variable is always integer, and is not an element of the tuple but is an index at which to find an element. That's why the expression **atoms[i]** is used inside the loop instead of simply **i** as before.

3.3.2 Membership

Tuples are not sets in the mathematical sense, because an element can belong to a tuple more than once, and there is an order to the elements. However, some set operations could be implemented using tuples by looking at individual elements (set union and intersection, for example). The *intersection* of two sets A and B is the set of elements that are members of A and also members of B. The membership operator for tuples is the key word **in**:

If 1 is in tuple1, the intersection of A and B, where A and B are tuples, is found using the following code:

```
for i in A:
      if i in B:
            C = C + i
```

The tuple C is the intersection of A and B. It works by taking each known element of A and testing to see if it is a member of B; if so, it is added to C.

Problem: What even numbers less than or equal to 100 are also perfect squares?

This could be expressed as a set intersection problem. The set of even numbers less than 100 could be enumerated (this is not actual code):

A = 2,4,6,8,10 … and so on

Or could be generated within a loop:

```
A = ()                        # Start with an empty tuple
for i in range(0,51):         # for appropriate integers
    A = A + (i*2,)            # add the next even number
                              # to the tuple
# Can't simply use A+i because i is integer, not a tuple.
```

Similarly, the perfect squares could be enumerated,

```
B = (4,9,16,25,36,49,64,81,100)
```

or, again, created in a loop:

```
B = ()
for i in range(0,11):
    B = B + ((i*i),)
```

Now set A can be examined, element by element, to see which members also belong to B:

```
C = ()
for i in A:
   if i in B:
      C = C + (i,)
```

The result is (0, 4, 16, 36, 64, 100).

Two important lessons are learned from this example. First, when constructing a new tuple from components, one can begin with an empty tuple. Second, individual components can be added to a tuple using the concatenation operator +, but the element should be made into a tuple with one component before doing the concatenation.

3.3.3 Delete

A tuple is *immutable*, meaning that it cannot be altered. Individual elements can be indexed but not changed or deleted. What can be done is to create a new tuple that has new elements; in particular, deleting an element means creating a new tuple that has all of the other elements except the one being deleted.

Problem: Delete the element lithium from the tuple *atoms*, along with its atomic number.

Going back to the tuple **atoms**, deleting one of the components – in particular, *Lithium* – begins with determining which component *Lithium* is; that is, what is its index? Start at the first element of the tuple and look for the string *Lithium*, stopping when it is found.

```
for i in range(0, len(atoms)):
    if atoms[i] == "Lithium":     # Found it at location i
       break;
    else:
       i = -1                     # not found
```

Knowing the index of the element to be deleted, it is also known that all elements before that one belong to the new tuple and all elements after it do, too. The elements before element **i** can be written as **atoms[0:i]**. Each element consists of a string and an integer, and assuming that both are to be deleted means that the elements following element **i** are **atoms[i+2:]**. In general, to delete one element, the second half would be **atoms[i+1:].** The end of the code snippet for deleting *Lithium* is as follows:

```
if i>=0:
    atoms = atoms[0:i] + atoms[i+2:]
```

The tuple **atoms** has not been altered so much as it has been replaced completely with a new tuple that has no *Lithium* component.

3.3.4 Update

Again, because a tuple is *immutable*, individual elements cannot be changed. A new tuple can be created that has new elements; in particular, updating an element means creating a new tuple that has all of the other elements except the one being updated, and that includes the new value in the correct position.

Problem: Change the entry for *Lithium* to an entry for *Oxygen*.

An update is usually a deletion followed by the insertion or addition of a new component. A deletion was done in the previous section, so what remains is to add a new component where the old one was deleted. Inserting the element *Oxygen* in place of *Lithium* would begin in the same way as the simple deletion already implemented:

```
for i in range(0, len(atoms)):
    if atoms[i] == "Lithium":      # Found it at location i
        break;
else:
    i = -1                         # not found
```

Next, a new tuple for *Oxygen* is created:

```
newtuple = ("Oxygen", 8)
```

And finally, this new tuple is placed at location **i** while *Lithium* is removed:

```
if i>=0:
    atoms = atoms[0:i] + newtuple + atoms[i+2:]
```

However, an update may not always involve a deletion. If *Lithium* is not a component of the tuple **atoms**, then perhaps *Oxygen* should be added to **atoms** anyway. Where? How about at the end?

```
else:     # If i is -1 then the new tuple goes at the end
    atoms = atoms + newtuple
```

3.3.5 Tuple Assignment

One of the unique aspects of Python is the *tuple assignment*. When a tuple is assigned to a variable, the components are converted into an internal form (that is, the one tuples always use). This is called tuple *packing*:

```
atoms=("Hydrogen",1,"Helium",2,"Lithium",3,"Beryllium",4,
       "Boron",5,"Carbon",6)
```

What is really interesting is that tuple *unpacking* can also be used. Consider the tuple:

```
srec = ('Parker', 'Jim', 1980, 'Math 550', 'C+', 'Cpsc 302',
        'A+')
```

which is a tuple packing of a student record. It can be unpacked into individual variables in the following way:

```
(fname, lname, year, cmin, gmin, cmax, gmax) = srec
```

Which is the same as

```
fname = srec[0]
lname = srec[1]
year  = srec[2]
cmin  = srec[4]
gmin  = srec[5]
cmax  = srec[6]
gmax  = srec[7]
```

Of course, the implication is that N variables can be assigned the value of N expressions or variables simultaneously if both are written as tuples. Examples are as follows:

```
(a, b, c, d, e) = (1,2,3,4,5)
(f, g, h, i, j) = (a, b, c, d, e)
```

The expression

```
(f, g, h, i, j) = 2 ** (a,b,c,d,e)
```

is invalid because the left side of ** is not a tuple, and Python won't convert 2 into a tuple. Also,

```
(f, g, h, i, j) = (2,2,2,2,2) ** (a,b,c,d,e)
```

is invalid because ** is not defined on tuples, nor are other arithmetic operations. As with strings, + means concatenation, though, so (1,2,3) + (4,5,6) yields (1,2,3,4,5,6).

Exchanging values between two variables is a common thing to do. It's an essential part of a sorting program, for example. The exchange in many languages requires three statements because a temporary copy of one of the variables has to be made during the swap:

```
temp = a
a = b
b = temp
```

Because of the way that tuples are implemented, this can be performed in one tuple assignment:

```
(a,b) = (b,a)
```

This is a little obscure, even to experienced programmers. A Java programmer could see what was meant, but initially, the rationale would not be obvious. This statement deserves a comment such as "perform an exchange of values using a tuple assignment."

3.3.6 Built-in Functions for Tuples

As examples for the table below, use the following:

```
T1 = (1,2,3,4,5)
T2 = (-1,2,4,5,7)
```

Table 3.2
Tuple Methods and their explanations

Function	Explanation (What Is Returned?)	Example
`len(T1)`	Gives the number of components that are members of T1.	`len(T1) == 5`
`max(T1)`	Returns the largest element that is a component of T1.	`max(T1) == 5` `max(T2) == 7`
`min(T1)`	Returns the smallest element that is a component of T1.	`min(T1) == 1` `min(T2) == -1`

In addition, tuples can be compared using the same operators as for integers and strings. The comparison is done on an element-by-element basis, just as it is with strings. In the example above, **T1>T2** because at the first location where the two tuples differ (the initial component) in the element in **T1** is greater than the corresponding element in **T2**. It is necessary for the corresponding elements of the tuple to be comparable; that is, they need to be of the same type. So if the tuples **t1** and **t2** are defined as

```
t1 = (1, 2, 3, "4", "5")
t2 = (-1,2,4,5,7)
```

then the expression **t1>t2** is not allowed. A string cannot be compared against an integer, and element 3 of **t1** is a string, whereas element 3 of **t2** is an integer.

3.4 LISTS

One way to think of a Python *list* is that it is a tuple in which the components can be modified. They have many properties of an array of the sort one might find in Java or C, in that they can be used as a place to store things and have random access to them; any element can be read or written. They are often used as one might use an array, but have a greater natural functionality.

Initially a list looks like a tuple, but uses square brackets to delimit it.

```
list1 = [2, 3, 5, 7, 11, 13, 17, 19]  # Prime numbers under 20
list2 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
list3 = ["hi", "ohio", "salut"]
```

A list can be empty:

```
list4 = []
```

and because they are like tuples and strings, each element in a list has an index, and they begin (as usual) at 0. Lists can be indexed and sliced, as before:

```
list1[2:4] is [5, 7]
```

The concatenation is like that of strings, too:

```
list6 = list1 + [23, 31]
```

yields [2, 3, 5, 7, 11, 13, 17, 19, 23, 31]

Negative values index from the end of the string. However, unlike strings and tuples, individual elements can be modified. So

```
list1[2] = 6
```

results in **list1** being [2, 3, 6, 7, 11, 13, 17, 19]. Also,

```
list3[1:] = "bonjour"
```

results in **list3** taking the value *oops*; it becomes

```
['hi', 'b', 'o', 'n', 'j', 'o', 'u', 'r'].
```

That's because a string is a sequence, too, and this string consists of seven components. Each component of the string becomes a component of the list. If the string "bonjour" is supposed to become a single component of the list, then it needs to be done this way:

```
list3[1:] = ["bonjour"]
```

The other components of **list3** are sequences, and now so is the new one. However, integers are *not* sequences, and the assignment

```
list1[2] = [6,8,9]
```

results in the value of **list2** being

```
[2, 3, [6, 8, 9], 7, 11, 13, 17, 19]
```

There is a list within this list; that is, the third component of **list1** is not an integer, but is a list of integers. That's legitimate, and works for tuples as well, but may not be what is intended.

Problem: Compute the average (mean) of a list of numbers.

The mean is the sum of all numbers in a collection divided by the number of numbers. If a set of numbers already exists as a list, calculating the mean might involve a loop that sums them followed by a division. For example, assuming that **list1** = [2, 3, 5, 7, 11, 13, 17, 19]:

```
mean = 0.0
for i in list1:
    mean = mean + i
mean = mean/len(list1)
```

A list can be used in a loop to define the values that the loop variable **i** takes on, a similar situation to that of a tuple. A second way to do the same thing would be

```
mean = 0.0
for i in range(0,len(list1)):
    mean = mean + list1[i]
mean = mean/len(list1)
```

In this case, the loop variable **i** is an index into the list and not a list element, but the result is the same. Python lists are more powerful than this, and making use of the extensive power of the list simplifies the calculation:

```
mean = sum(list1) / len(list1)
```

The built-in function **sum** calculates and returns the sum of all of the elements in the list. That was the purpose of the loop, so the loop is not needed at all. The functions that work for tuples also work for lists (**min**, **max**, **len**), but some of the power of lists is in the methods it provides.

3.4.1 Editing Lists

Editing a list means to change the values within it, usually to reflect a new situation to be handled by the program. The most obvious way to edit a list is to simply assign a new value to one of the components. For example,

```
list2 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
list2[0] = "Nitrogen"
print (list2)
```

results in the following output:

['Nitrogen', 'Helium', 'Lithium', 'Beryllium', 'Boron', 'Carbon']

This substitution of a component is not possible with strings or tuples. It is possible to replace a single component with another list:

```
list2 = ["Hydrogen","Helium","Lithium","Beryllium",
         "Boron","Carbon"]
list2[0] = ["Hydrogen", "Nitrogen"]
```

results in

```
list2 = [['Hydrogen','Nitrogen'],'Helium','Lithium',
          'Beryllium','Boron','Carbon']
```

3.4.2 Insert

The **insert** method is not normally what is thought of as an insertion. We use the **insert** method to place new components within a list. This method places a component at a specified index; that is, the index of the new element will be the one given. To place “Nitrogen” at the beginning of list2, which is index 0,

```
list2.insert(0, "Nitrogen")
```

The first value given to **insert**, 0 in this case, is the index at which to place the component, and the second value is the thing to be inserted. Inserting “Nitrogen” at the end of the list would be accomplished by

```
list2.insert(len(list2), "Nitrogen)
```

However, consider this:

```
list2.insert(-1, "Nitrogen)
```

Will this insert “Nitrogen” at the end? No. At the beginning of the statement, the value of **list2[-1]** is “Carbon.” This is the value at index 5. Therefore, the insert of “Nitrogen” will be at index 5, resulting in

[‘Hydrogen’, ‘Helium’, ‘Lithium’, ‘Beryllium’, ‘Boron’, ‘Nitrogen’, ‘Carbon’]

3.4.3 Append

Another way to add something to the end of a list is to use the **append** method:

```
list2.append("Nitrogen")
```

Results in

[‘Hydrogen’, ‘Helium’, ‘Lithium’, ‘Beryllium’, ‘Boron’, ‘Carbon’, ‘Nitrogen’]

Remember, the + operation only concatenates a list to a list, so the equivalent expression involving + is

```
list2 = list2 + ["Nitrogen"]
```

3.4.4 Extend

The **extend** method does almost the same things as the + operator. With the definitions

```
a = [1,2,3,4,5]
b = [6,7,8,9,10]
```

```
print (a+b)
a.extend(b)
print(a)
```

The output is

[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]

However, if **append** has been used instead of **extend** above,

```
a = [1,2,3,4,5]
b = [6,7,8,9,10]
print (a+b)
a.append(b)
print(a)
```

The result would have been

[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
[1, 2, 3, 4, 5, [6, 7, 8, 9, 10]]

3.4.5 Remove

The remove method does what is expected: it removes an element from the list. But unlike insert, for example, it does not do it using an index; the value to be remove is specified.

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
list1.remove("Helium")
```

results in the **list1** being [‘Hydrogen’, ‘Lithium’, ‘Beryllium’, ‘Boron’, ‘Carbon’]. Unfortunately, if the component being deleted is not a member of the list, then an error occurs. There are ways to deal with that, or a test can be made for trying to delete an item:

```
if "Nitrogen" in list1:
    list1.remove("Nitrogen")
```

If there is more than a single instance of the item being removed, then only the first one is removed.

3.4.6 Index

When discussing tuples, we noted that the **index** method looked through the tuple and found the index at which a specified item occurred. The **index** method for lists works in the same way.

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
print (list1.index("Boron"))
```

prints "4," because the string "Boron" appears at index 4 in this list (starting from 0, of course). If there is more than one occurrence of "Boron" in the list, then the index of the first one (i.e., the smallest index) is returned. If the value is not found in the string, then an error occurs. It might be appropriate to check:

```
if "Boron" in list1:
    print (list1.index("Boron"))
```

3.4.7 Pop

The **pop** method is effectively the reverse or inverse of **append**. It removes the last item (i.e., the one with the largest index) from the list. If the list is empty, then an error occurs. For example,

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
list1.pop()
print (list1)
```

prints the result

['Hydrogen', 'Helium', 'Lithium', 'Beryllium', 'Boron']

To avoid the error that can occur if the list is empty, simply check to see that the length of the list is greater than zero before using **pop**:

```
if len(list1) > 0:
    list1.pop()
```

The method is called **pop** because it represents a way to implement the operation of the same name on a data structure called a *stack*.

3.4.8 Sort

This method places the components of a list into ascending order. We use the **list1** variable that has been used so often for the following code:

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
list1.sort()
print(list1)
```

The result is

['Beryllium', 'Boron', 'Carbon', 'Helium', 'Hydrogen', 'Lithium']

which is in alphabetic order. The method sorts integers and floating point numbers, as well. Strings and numbers cannot be mixed, though, because they cannot be compared. So

```
list2 = ["Hydrogen",1,"Helium",2,"Lithium",3,"Beryllium",4,
         "Boron",5]
list2.sort()
```

results in an error that is something like

```
    list2.sort()
TypeError: unorderable types: int() < str()
```

The meaning of this error should be clear. Things of type **int** (integer) and things of type **str** (string) cannot be compared against each other and so cannot be placed in a sensible order if mixed. For sort to work properly, all of the elements of the list must be of the same type. It is always possible to convert one type of thing into another, and in Python converting an integer to a string is accomplished with the **str()** function; a string is converted into an integer using **int()**. **str(3)** would result in "3," and **int("12")** is 12. An error will occur if it is not possible, so **int(12.2)** will fail.

If each element of a list is itself a list, it can still be sorted. Consider the following list:

```
z = [["Hydrogen",3],["Hydrogen",2],["Lithium",3],
     ["Beryllium",4],["Boron",5]]
```

When sorted this becomes:

```
[['Beryllium',4],['Boron',5],['Hydrogen',2],['Hydrogen',3],
 ['Lithium',3]]
```

Each component of this list is compatible with the others, consisting of a string and an integer. Thus, they can be compared against each other. Notice that there are two entries for hydrogen: one with a number 2 and one with a number 3. The **sort** method arranges them correctly. A list is sorted by individual elements in sequence order, so the first thing tested would be the string. If those are the same, then the next element is checked. That's an integer, so the component with the smallest integer component will come first.

3.4.9 Reverse

In any sequence, the order of the components within it is important. Reversing that order is a logical operation to provide, but may not be used very often. One instance where it can be important is after a sort. The **sort** method always places components into *ascending* order. If they are supposed to be in *descending* order, then the **reverse** method becomes valuable. As an example, consider sorting the list **q**:

```
q = [5, 6, 1, 5, 4, 9, 9, 1, 6, 3]
q.sort()
```

The value of **q** at this point is

[1, 1, 3, 4, 5, 5, 6, 6, 9, 9]

To place this list in descending order, the reverse method is used:

```
q.reverse()
```

and the result is

[9, 9, 6, 6, 5, 5, 4, 3, 1, 1]

It is hard to say whether ascending order is needed more often than descending order. Names are often sorted smallest first (ascending), but dates are more likely to require more recent dates before later ones (descending).

3.4.10 Count

The **count** method is used to determine how many times a potential component of a list actually occurs. It does not return the number of elements in the list – that job is done by the **len** function. We use the list **q** as an example:

```
q = [5, 6, 1, 5, 4, 9, 9, 1, 6, 3]
print  (1,q.count(1),  2,  q.count(2),  3,  q.count(3),  99,
q.count(99))
```

This code results in the output

1 2   2 0   3 1   99 0

where the spacing is enhanced for emphasis. This says that there are 2 instances of the number 1 (1,2) in the list, zero instances of 2 (2,0), one instance of the number 3 (3,1), and none of 99 (99,0).

3.4.11 List Comprehension

Two mechanisms were discussed for creating a list of items. The first is to use constants, as in the list **q** in the previous section. The second appends items to a list, and this could be done within a loop. Making a list of perfect squares could be done like this:

```
t = []
for i in range(0,10):
    t = t + [i*i]
```

which creates the list [0, 1, 4, 9, 16, 25, 36, 49, 64, 81]. This kind of approach is common enough that a special syntax has been created for it in Python – the *list comprehension*.

The basic idea is simple enough, although some specific cases are complicated. In the situation above involving perfect squares, the elements in the list are some function of the index. When that is true, the loop, index, and function can be given within the square brackets as a definition of the list. The list **t** could be defined as

```
tt = [i**2 for i in range(10)]
```

The **for** loop is within the square brackets, indicating that the purpose is to define components of the list. The variable **i** here is the loop variable, and **i****2** is the function that creates the elements from the index. This is a simple example of a list comprehension.

We create random integer values with the following code:

```
tt = [random.randint(0,100) for i in range(10)]
```

We can put the first six elements in all uppercase letters, as well:

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
ss = [i.upper() for i in list1]
```

This is a very effective way to create lists, but it does depend on having a known connection between the index and the element.

3.4.12 Lists and Tuples

A tuple can be converted into a list. Lists have a greater functionality than tuples; that is, they provide more operations and greater ability to represent data. However, they are more complicated and require more computer resources. If something can be represented as a tuple, then it is likely best to do so. A tuple is designed to be a collection of elements that as a whole represent some more complicated object, but that individually are perhaps of different types. This is rather like a C *struct* or Pascal *record*. A list is more often used to hold a set of elements that all have the same type, more like an array. This is a good way to think of the two types when deciding what to use to solve a specific problem.

Python provides tools for conversion. The built-in function **list** takes a tuple and converts it into a list; the function tuple does the reverse, taking a list and turning it into a tuple. For example, converting list1 into a tuple involves the following code:

```
tuple1 = tuple(list1)
print(tuple1)
```

This code yields

('Hydrogen', 'Helium', 'Lithium', 'Beryllium', 'Boron', 'Carbon')

This is seen to be a tuple because of the "(" and ")" delimiters. The reverse operation

```
v = list(tuple1)
print(v)
```

prints the text line

['Hydrogen', 'Helium', 'Lithium', 'Beryllium', 'Boron', 'Carbon']

and the square brackets indicate this is a list.

3.4.13 Exceptions

Exceptions are the usual way to check for errors of indexing and membership in lists. The error is allowed to occur, but an exception is tested and handled in the case where, for example, an item being deleted is not in the list.

Problem: Delete the element Helium from a list.

Earlier, as an example of the **remove** method, a program snippet was written to delete the element *Helium* from a list of elements.

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
if "Helium" in list1:
    list1.remove("Helium")
```

Because the list list1 may not have *Helium* as one of the components a check was made before an attempt to delete it. An attempt to delete an element from a list where the element does not appear in that list results in an **AttributeError**. Rather than perform an explicit test, a Python programmer would more likely use an exception here. The error can be caught as follows:

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
try:
    list1.remove("Helium")
except:
   print ('Can't find Helium')
```

The advantage of this over allowing the error to occur is that the program can continue to execute.

Problem: Delete a specified element from a list.

Given the same list, read an element from the keyboard and delete that element from the list. The basic code is the same, but now the string is entered and could be anything at all. It's easier to test a program when it can be made to fail on purpose. The name is entered using the **input** function and is used as the parameter to **remove**. Now it is possible to test all of the code in this program without changing it. First, here is the program:

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
```

```
s = input("Enter:")
try:
    list1.remove(s)
except:
   print ('Can't find ', s)
print (list1)
```

Properly testing a program means executing all of the statements that comprise it and ensuring that the answer given is correct. In this case, first delete an element that is a part of the list. Try Lithium. Here is the output:

Enter: Lithium

['Hydrogen', 'Helium', 'Beryllium', 'Boron', 'Carbon']

This is correct. These are the statements that were executed in this instance:

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
s = input("Enter:")
try:
    list1.remove(s)  # This was successful
print (list1)
```

Now try to delete "Oxygen." The output is

Enter: Oxygen

Can't find Oxygen

['Hydrogen', 'Helium', 'Lithium', 'Beryllium', 'Boron', 'Carbon']

This is correct. These statements were executed:

```
list1 = ["Hydrogen","Helium","Lithium","Beryllium","Boron",
         "Carbon"]
s = input("Enter:")
try:
    list1.remove(s)    # this was not successful
except:
   print ('Can't find ', s)
print (list1)
```

All of the code in the program has been executed and the results checked for both major situations. For any major piece of software this kind of testing is exhausting, but it is really the only way to minimize the errors that remain in the final program.

3.5 SET TYPES

Something of type *set* is an unordered collection of objects. An element can only be a member of a given *set* once, so in that sense it is much like a mathematical set. In fact, that's the point. Because a set is unordered operations, indexing and slicing are not provided. Python does support membership (**is**), size (**len()**), and looping on membership (for **i** in **set**).

Mathematical sets have certain specific, well-defined operations, and those are available on a Python set also.

Subset	**set1 < set2** means **set1** is a true subset of **s2**.
Intersection	**set1 & set2** creates a new set containing members in common with both.
Union	**set1 | set2** creates a new set with all elements of both.
Difference	**set1-set2** creates a new set with members that are not in both.
Equality	**set1==set2** is true if both sets contain only the same elements.

Creating a new object of type *set* is a matter of specifying either that it is a *set* or what the elements are. One way is to use the {} syntax:

```
set1 = {1,3,5,7,9}
```

or to use the constructor

```
set2 = set(range(1, 10))
```

which gives the set {1, 2, 3, 4, 5, 6, 7, 8, 9}. Therefore,

set1<set2 is True

set1 & set2 is {9, 1, 3, 5, 7} (Note: Order does not matter to a set.)

set1 | set2 is {1, 2, 3, 4, 5, 6, 7, 8, 9}

set2 – set1 is {8, 2, 4, 6}

A new element can be added to a set using **add()**:

```
set1.add(11)
```

and removed using **remove()**:

```
set1.remove(11)
```

or **discard()**:

```
set1.discard(11)
```

If the element being removed is not in the set, then an error will occur (*KeyError*) when **remove()** is called, but not with **discard()**. This should be tested first or be placed in an **except** statement.

All of the examples so far involve integers belonging to a set, but other types can belong as well: floating point numbers, strings, and even tuples (not *lists*). For example, the following are legal sets:

```
{"a", "e", "i", "o", "u"}
{"cyan", "yellow", "magenta"}
{(2,4), (3,9), (4,16), (5,25), (6,36), (7,49)}
```

3.5.1 Example: Craps

Craps is a dice game, and it commonly involves betting on the outcome. The player (*shooter*) rolls two dice. If, on the first roll (*pass*), a total of 7 or 11 is obtained, then the shooter wins. An initial roll of 2, 3, or 12 loses immediately. Any other roll is called the *point*. In that case, the shooter continues to roll the dice. If a 7 is obtained, then the shooter loses, and if the point number is rolled, then the shooter wins. The shooter continues to roll until on or the other occurs. One way to implement this game in Python is to use sets.

Elements of the sets are the values on each die, which is to say one roll. There are two dice, so a total of 36 combinations exist. A single roll is a tuple, such as (1,1) or (3,4). There are only 12 distinct sums of two dice, and multiple ways to achieve them. A sequence named **roll** is created that contains a set for each possible value, and that set contains all of the ways that the value can be obtained. For instance, there are two ways to roll a 3, so

```
roll[3] = {(1,2), (2,1)}
```

Initially, a set is created for each possible roll of a pair of dice and then is initialized as described:

```
from random import *

roll = list(range(0,13))       # Create the empty list
for i in range(1,13):          # and fill with empty sets.
    roll[i] = set()

for i in range (1,7):           # Now for each possible roll
    for j in range (1,7):       # of two dice, add that roll
        k = i+j                 # to the element of roll for
        roll[k].add( (i,j) )    # that value (sum of the
                                # dice)
```

Now **roll[i]** contains all of the ways to roll a value of **i**. In particular, **roll[7]** contains all ways to roll a 7 and **roll[11]** contains all ways to roll an 11. Thus, all of the rolls that win on the first pass can be placed in a single set, the union of **roll[7]** and **roll[11]**:

```
winner = roll[7] | roll[11]
```

Similarly, the rolls that will lose for the shooter on the first pass are as follows:

```
loser = roll[2] | roll[3] | roll[12]
```

If any other roll is thrown, then that becomes the point. Roll the die amount to get a random number between 1 and 6, inclusive, or

```
die1 = randrange(1,7)
die2 = randrange(1,7)
```

Remember that **randrange()** produces a number *less* than the second parameter. Given this roll, the point is the set **roll[die1+die2]**. Continuing the program from the die rolls:

```
val = (die1,die2)               # A tuple, the current roll
print ("Shooter rolls ", val)
if val in winner:               # Is this tuple a winner?
    print ("The shooter wins!")
elif val in loser:              # Is it a loser?
    print ("The shooter loses")
else:
    point = roll[die1+die2]     # Define the point set
    print (die1+die2, " is your point.")
```

Now the dice are rolled repeatedly. If the roll is in the point set, then the shooter wins. If the roll is a 7 (in the set **roll[7]**), then the player loses. Otherwise the shooter rolls again.

```
while True:                    # Repeat until a win or
                               #loss happens
    die1 = randrange(1,7)      # Roll the dice
    die2 = randrange(1,7)
    val = (die1, die2)         # val is a tuple
    print ("Rolls ", val)
    if val in roll[7]:         # Any 7 roll loses
        print ("The shooter loses!")
        break
    if val in point:           # Rolling the 'point' wins.
        print ("The shooter makes the point. A winner!")
        break
```

In a real craps game, this entire process is repeated, and bets are placed on each individual game as to whether the player will win or lose.

3.6 SUMMARY

A variable can have a type, which could be a list or sequence of other, simpler things. Using variables having these types is an essential part of writing useful and effective code. Python offers strings, tuples, and lists as objects that consist of multiple parts. They are called *sequence* types.

A *string* is a sequence of characters. The word *sequence* implies that the order of the characters within the string matters, and that is true of a string. Strings most often represent the way that communication between a computer and a human takes place. A string can be indexed to see what character is in any position (e.g., **s[i]**), can be searched for a string that occurs with it, can have characters concatenated to it, and can be used in many other useful operations. If a string **s** contains an integer, then **int(s)** yields that integer, and **str(i)** creates a string from an integer, **i**.

A *tuple* is almost identical to a string in basic structure, except that it is composed of arbitrary components instead of characters. Examples are **tup1 = (2, 3, 5)** and **tup2 = ("Hydrogen","Helium","Carbon")**. A tuple can contain mixed type, such as integers and strings: **tup3 = ("star", 1, "planet", 2)**. An element of a tuple cannot be altered, so it is said to be *immutable*, although concatenation is possible.

A *list* is like a tuple but is not immutable, so individual elements can be modified. A list uses square brackets as a delimiter, instead of parentheses as used for a tuple. Changing an element involves indexing it, so if **list1** is a list then **list1[2] = 6** modifies element 2 of that list.

A *set* is an unordered collection of objects. An element can be almost any type, but can only occur in a set once. This mimics a mathematical set. Elements can be added and removed, and the set operations *union*, *intersection*, and *difference* can be performed.

Exercises

For the exercises below, assume the following definitions:

```
str1 = "okra is the closest thing to nylon i've ever eaten."
str2 = "pull the string, and it will follow wherever you
        wish."
str3 = "let out a little more string on your kite."
str4 = "every string is a different color, a different
        voice."
vowels = 'aeiou'
atoms=("Hydrogen",1,"Helium",2,"Lithium",3,"Boron",5,
       "Carbon",6, "Oxygen",8)
```

1. What is printed by the following code snippets?

a.
```
for i  in range(0,len(str3)):
     print (str3[i], end='')
```

b.
```
for for i  in range(0,len(str3)):
      print (i, end='')
```

c.
```
for i  in range(0,len(str3)):
     print (str2[i], end='')
```

d.
```
for i  in str3:
     print (i, end='')
```

e.
```
for i  in str3:
     if i in vowels:
        print(i, end='')
```

f.
```
for i  in str1:
    if not(i in vowels):
        print(i, end='')
```

2. Construct a loop that prints out all characters of **str4** that correspond to a vowel in **str3**. Note: the two strings are different lengths.

3. A *Caesar cypher* is a way to transmit a secret message. When encoding a message, each character is replaced by one that is a fixed distance further along the alphabet. If that distance is 6, for example, the letter "a" would be replaced by "g," which is 6 positions further along. The characters at the end wrap around to the beginning, so "z" is "f." Write some Python code that encodes **str1** in this way. Ensure that it works by decrypting the following string:
"varr znk yzxotm, gtj oz corr lurruc cnkxkbkx eua coyn."

Ans: uqxg oy znk iruykyz znotm zu terut o'bk kbkx kgzkt.

4. Write a Python snippet that creates two tuples from the single tuple **atoms**: one named **elements**, which contains only the names, and one called **numbers**, which contains the atomic numbers of the elements in the tuple **atoms**.

5. Write a Python program that reads numbers from the keyboard and appends them to a tuple. Stop the process when a negative number is entered and then print the tuple that was created.

6. A deck of playing cards consists of 52 items: each one has one of four suits (clubs, diamonds, hearts, and spades) and within each suit values from 1-10, and the jack, queen, and king. Write a Python program that creates a deck of cards, shuffles them, and prints out the result.

7. Write a Python program that reads names (single words) one at a time from a keyboard and deletes them from a list named **names** where they are already elements of that list. If the name is not already a member of the list, then add it. Typing the word "quit" terminates the program.

8. Assume that a string named **temp** exists and has a value. Write Python code that prints **temp** backwards.

9. A palindrome is a phrase (a string) that reads the same forwards and backwards. The name Hannah is a palindrome; so is Ogopogo, the name of a monster that lives in lake Okanogan. Write a Python program that determines whether a given string is a palindrome.

10. Most examples of palindromes contain spaces and punctuation, and these characters are ignored when deciding whether the phrase is palindromic. So is case. Thus, the phrase "I prefer pi" is a palindrome. With these considerations in mind, write a Python program that determines whether a string is a palindrome.

Notes and Other Resources

Built-intypes:*https://docs.python.org/3.4/library/stdtypes.html?highlight=set#set*

Python strings: *https://docs.python.org/3/library/string.html*

Rules of Craps: *http://www.bigmcasino.com/learn-more/learn-to-play-craps/what-are-the-basic-rules-of-craps/*

1. David Mertz (2003). *Text Processing in Python,* Addison Wesley Professional, ISBN-13: 978-0321112545.
2. David Makinson (2012). *Sets, Logic and Maths for Computing*, Springer; 2nd ed. ISBN-13: 978-1447124993.
3. J. D. Oldham (2005). "What happens after Python in CS1?" *Journal of Computing Sciences in Colleges*, *20*(6), 7–13.

CHAPTER 4

FUNCTIONS

In this chapter

There is a large and useful set of functions built in to Python. These are sometimes simply there for the using, like **print** and **input**, and sometimes are part of a module that must be imported, and like **random**. However large this collection of functions is, it is impossible that it will include everything that every programmer needs. At some point, there will be a need to create a function that does something new, and Python should permit this.

Why would a programmer want to create a function of their own? It is partly a principle of "reduce, re-use, or recycle." Functions are all about code re-use. If some section of code can be invoked as a function instead of being repeated many times, then there will be less typing involved. It is also to support more correct programs: a small code unit like a function can be very thoroughly tested and nearly guaranteed to be correct. It is also to promote the use of *working* code: once a function is tested, it can be placed in a collection of code (module) and used again instead of being re-written many times.

A function is really just some code that has a name, and can be executed simply by invoking that name. It usually represents some task that has to be done fairly frequently, but that's not a requirement. Some functions are invoked (or *called*) only once. In this context a function is a way to break up a long piece of code into many shorter pieces which, as has been pointed out, are easier to test and maintain.

A function should also have one single task, or at least one main task. That task should be represented in the function name. A function named *maximum* should have the task of locating the maximum of something; a function named *cosine* should calculate the cosine of an angle. A function named *wilma* tells another programmer who is reading the code nothing about what the program is doing, and if a function named *cosine* computes the square root of a number, then it is not just uninformative, but misleading. There is a social compact between programmers that says that you should be as clear as possible about what your code is doing.

The fact that many functions return a value has been skipped over, but it is a key part of the function construct. The code within the function has a purpose, and often that purpose is concentrated in the return value. However it works, and whatever the code looks like, the purpose of the *cosine* function is to return a single value that is the mathematical cosine of a given angle. The nature of the function is encapsulated in that value. There are some functions that do not explicitly return a value; such a function might be called to print an error message or draw a graphical object in a window. Even if it is not specifically declared in the definition, all functions return *something*. If that something is not defined, then the function returns a value called **None**.

How can functions be declared and used in Python?

4.1 FUNCTION DEFINITION: SYNTAX AND SEMANTICS

Unlike in the cases of **if** statements or **for** statements, a function definition does not involve the word "function." As an example of a simple definition in Python, imagine a program that needs a function to print twenty # characters on a line. It could be defined as follows:

```
def pound20 ():
    for i in range(0,20):
        print ("#", end="")
```

The word **def** always begins the definition of a function. This is followed by the name of the function, in this case, **pound20**, because the function prints 20 *pound* characters (also known as a *hash* character or *octothorpe*). Then comes the list of parameters, which can be thought of as a tuple of variable names. In this case, the tuple is empty, meaning that nothing is passed to the function. Finally, we use the : character that defines a new suite that comprises the code belonging to the function. Now, the code is indented one more level, and when the indentation reverts to the original level, the function definition is complete.

Calling this function is a matter of using its name as a statement or in an expression, being careful to always include the tuple of the parameters. Even when the tuple is empty, it helps distinguish a function from a variable. A call to this function would be as follows:

```
pound20 ()
```

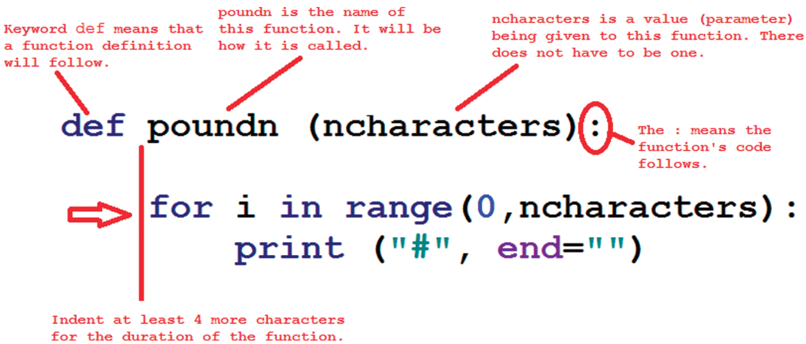


Figure 4.1
The syntax of a function definition.

The result is that 20 # characters are printed on one line of the output console.

A function can be given or *pass* one or more values that will determine the result of the function. A function **cosine**, for example, would be passed an angle, and that angle would be used to compute the cosine. Each call to **cosine** passing a different value can yield a different result. In the case of the function that prints pound characters it might be useful to pass it the number of pound characters to print. It should not be called **pound20** anymore because it does not always print 20 characters. It is called **poundn** this time:

```
def poundn (ncharacters):
    for i in range(0,ncharacters):
        print ("#", end="")
```

The variable **ncharacters** that is given in parentheses after the function name is called a *parameter* or an *argument*, and indicates the name by which the function refers to the value passed to it. This name is known only inside of the function, and while it can be modified within the function, this modification does not have any bearing on anything outside. The call to **poundn** must now include a value to be passed to the function:

```
poundn (3)
```

When this call is performed, the code within **poundn** begins executing, and the value of **ncharacters** is 3, the value that was passed. It prints 3 characters and returns. A subsequent call to **poundn** could be passed a different number, perhaps 8, and then **ncharacters** would take on the value 8 and the function would print 8 characters. It will print as many characters as requested through the parameter

4.1.1 Problem: Use the function *poundn* to Draw a Histogram

In Chapter 2, a simple histogram was created from some print statements and loops. The same code was repeated many times, one for each histogram bar. As it happens, the character used to draw the histogram bars was the pound character, so the function **poundn** could be used as a basis for a histogram program. Here is the output that is desired:

```
Earnings for WidgetCorp for 2016
  Dollars for each quarter
 ==============================
Q1: ########      190000
Q2: ################      340000
Q3: ##########################################      873000
Q4: ####################      439833
```

Each pound character represents $20,000, and there are four variables that hold the profit for each of the four quarters: q1, q2, q3, and q4. Given these criteria, a solution using **poundn** would call the function four times, once for each quarter:

```
print ("Earnings for WidgetCorp for 2016")
print ("   Dollars for each quarter   ")
print (" ==============================")
q1 = 190000  # The dollar amounts for profits
q2 = 340000  # in each of the four quarters of 2016
q3 = 873000
q4 = 439833

print ("Q1: ", end="")
poundn(int(q1/20000))   # Raw dollar amount is divided by
                        # 20000 to yield the number of
                        # characters.
print ("     ", q1)

print ("Q2: ", end="")
poundn (int(q2/20000))
print ("     ", q2)

print ("Q3: ", end="")
poundn (int(q3/20000))
print ("     ", q3)

print ("Q4: ", end="")
poundn (int(q4/20000))
print ("     ", q4)
```

Each profit value must be scaled by dividing by 20,000, just as happened before. In this case, the resulting value is passed to **poundn**, indicting the number of #s to draw.

4.1.2 Problem: Generalize the Histogram Code for Other Years

Any company will need to do financial reports every year at least. Hiring a programmer to do this task on a computer is not a reasonable thing to do, because computers can be made to do this job in a very general way. For example, given that each year will have four quarters and each quarter will have a profit, why not store these data as a list? Each year will have one list containing four items, and the name of the variable could initially be related to the year:

```
profit2016 = [190000, 340000, 873000, 439833]
```

The profit for the first quarter is **profit2016[0]**, the second quarter is **profit2016[1]**, and so on. Using this variable means passing one of the elements of the list to **poundn** instead of a simple variable, but that is fine, it's a legal expression. So drawing the characters for the first quarter would be done with the following code:

```
poundn(int(profit2016[0]/20000))
```

Now consider what else gets printed. To print everything for the first quarter the code was:

```
print ("Q1: ", end="")
poundn(int(profit2016[0]/20000))
print ("     ", q1)
```

This means that the label on the left, Q1, the parameters to **poundn**, and the actual value of the profit are needed. All of these are available and can be provided within a simple loop. Assuming that the loop variable **i** runs from 0 to 3, the code within that loop that duplicates the previous example can be constructed one line at a time. In each iteration, the quarter is **i+1** because **i** starts at 0; convert that to a string and build the label "Q1 :" from it:

```
print (Q1: ", end="")
print ("Q"+str(i+1)+": ", end="")
```

This is probably the trickiest part. The label string is constructed from the letter "Q," a number between 1 and 4 indicating the quarter, and for the terminal string ":" . These are simply concatenated together in the **print** statement.

Now call **poundn** as before:

```
poundn(int(profit2016[i]/20000))
poundn(int(profit2016[i]/20000))
```

Finally, print the raw dollar value on the right:

```
print ("     ", q1)
print ("     ", profit2016[i])
```

Using this plan, the entire histogram can be drawn using only four statements:

```
for i in range(0,4):
    print ("Q"+str(i+1)+": ", end="")
    poundn(int(profit2016[i]/20000))
    print ("     ", profit2016[i])
```

There is another step. Since this will be done every year, create a function that takes the data and the year as parameters. This function is called **pqhistogram**:

```
def pqhistogram (profit, year):
    print ("Earnings for WidgetCorp for "+str(year))
    print ("   Dollars for each quarter   ")
    print (" ==============================")
    for i in range(0,4):
        print ("Q"+str(i+1)+": ", end="")
        poundn(int(profit[i]/20000))
        print ("     ", profit[i])
```

The function **pqhistogram** produces the same output as did the original program, and does so more generally and concisely. This function also brings to light two new ideas. One is that it is possible to pass more than one parameter to a function. The second is that it is possible to call a function from within another function; in this case, **poundn** is called from inside of **pqhistogram**. The call is made after defining the list that contains the profit values:

```
profit2016 = [190000, 340000, 873000, 439833]
pqhistogram (profit2016, 2016)
```

These parameters are positional; that is, the first value passed will correspond to the first name in the parameter list, and the second to the second. This is the default for functions with any number of parameters.

NOTE

A **def** *statement is not a declaration. Such things are foreign to Python. A* **def** *statement executes, and it creates a new function each time it is executed.*

4.2 FUNCTION EXECUTION

When a function is called, the first statement of that function starts to execute, and it continues, statement by statement, through the code until the last statement of that function or until it returns prematurely. When that last statement executes, then the execution continues from the place where it was *called*. As a function can be called from many places, Python has to remember where the function was called so that it can return. Parameters can be expressions or variables, and normally differ each time the function is called. Functions can also access variables defined elsewhere.

Most importantly, functions return values.

4.2.1 Returning a Value

All functions return a value, and as such can be treated within expressions as if they were variables having that value. Assuming the existence of a **cosine** function, it could be used in an expression in the usual ways. For example,

```
x = cosine(x)*r
if cosine(x) < 0.5:
     print (cosine(x)*cosine(x))
```

In these cases, the value returned by the function is used by the code to calculate a further value or to create output. The expression "cosine(x)" resolves to a value of some Python type. The most common purpose of a function is to calculate a value, which is then returned to the calling part of the program and can possibly be used in a further calculation. But how does a function get its value? In a **return** statement.

The return statement assigns a value and a type to the object returned by the function. It also stops executing the function and resumes execution at the location where the function was called. A simple example would be to return a single value, such as an integer or floating-point number:

```
return 0
```

returns the value 0 from a function. The return value could be an expression:

```
return x*x + y*y
```

A function has only one return value, but it can be of any type, so could be a list or tuple that contains multiple components:

```
return (2,3,5,7,11)
return ["fluorine","chlorine","bromine","iodine",
        "astatine"]
```

Expressions can include function calls, so a return value can be defined in this way as well; for example

```
return cosine(x)
```

One of the simplest functions that can be used as an example is one that calculates the square of its parameter.

```
def square (x):
    return x*x
```

The print statement

```
print (square(12))
```

prints

```
144
```

Interestingly, the statement

```
print(square(12.0))
```

prints

```
144.0
```

The same function returns an integer in one case and a float in the other. Why? Because the function returns the result of an expression involving its parameter, which in one case was integer and in the other was real. This implies that a function has no fixed type and can return any type at all. Indeed, the same function can have return statements that return an integer, a float, a string, and a list independent of type of the parameter passed:

```
def test (x):  # Return one of four types depending on x
    if x<1:
        return 1
    if x<2:
        return 2.0
    if x<3:
        return "3"
```

```
    return [1,2,3,4]

print (test(0))
print (test(1))
print (test(2))
print (test(3))
```

The output is as follows:

```
1
2.0
3
[1, 2, 3, 4]
```

Problem: Write a function to calculate the square root of its parameter.

Two thousand years ago, the Babylonians had a way to calculate the square root of a number. They understood the definition of a square root: that if **y*y = x,** then **y** is the square root of **x**. They figured out that if **y** was an over-estimate to the true value of the square root of **x**, then **x/y** would be an underestimate. In that case, a better guess would be to average those two values: the next guess would be **y**1 **= (y + x/y)/2**. The guess after that would be **y**2 **= (y**1**+x/y**1**)/2**, and so on. At any point in the calculation, the error (difference between the correct answer and the estimate) can be found by squaring the guess **y**i and subtracting x from it, knowing that **yi*yi** is supposed to equal **x**.

The function therefore starts by guessing what the square root might be. It cannot be 0, because then **x/y** would be undefined. **x** is a good guess. Then, we construct a loop based on the expression **y**2 **= (y**1**+x/y**1**)/2**, or more generally, **y**i+1 **= (yi+x/yi)/2** for iteration **i**. At first, run this loop a fixed number of times (here, we use 20 times).

```
def root (x):                 # Compute the square root of x
    y = x                     # First guess: too big,
                              # probably
    for i in range(1, 20):    # Iterate20 times
        y = (y + x/y)/2.0     # Average the prior guess
                              # and x/y
    return y                  # Return the last guess
```

This correctly computes the square root of 2 to 15 decimal places. This is probably more than is necessary, meaning that the loop is executing more times than it needs to. In fact, changing the 20 iterations to only 6 still gives 15 correct places. This is exceptional accuracy: if the distance between the Earth and the sun were known this accurately, it would be within 0.006 inches of the correct value. The Babylonians were very clever.

What's the square root of 10000? If the number of iterations is kept at 6, then the answer is a very poor one indeed: 323.1. Why? Some numbers (large ones) need more iterations than others. To guarantee that a good estimate of the square root is returned, an estimate of the error should be used. When the error is small enough, then the value is good enough. The error is **x-y**i***y**i. The function should not loop a fixed number of times, but instead should repeat until the error is less than, say, 0.0000001. This function is named **roote**, where the "e" is for "error."

```
# Computer the square root of X to 7 decimal places
def roote (x):
y = x                    # y is supposed to be the square
                         # root of x, so
e = abs(x-y*y)           # the error is x - y*y
while e > 0.0000001:     # repeat while the error is bigger
                         # than 0.0000001
  y = (y + x/y)/2.0      # New estimate for square root
  e = abs(x-y*y)         New error value
return y
```

This function will return the square root of any positive value of **x** to within 7 decimal places. It should check for negative values, though.

4.2.2 Parameters

A parameter can be either a name, meaning that it is a Python *variable* (object) of some kind, or an *expression*, meaning it has a value but no permanence in that it can't be accessed later on – it has no name. Both are passed to a function as an *object reference*. The expression is evaluated before being given to the function and its type does not matter in so far as Python will always know what it is; its value is assigned a name when it is passed. Consider, for example, the function **square** in the following context:

```
...
pi = 3.14159
r = 2.54
c = square (2*pi*r)
print ("Circumference is ", c)
```

The assignments to **pi** and **r** are performed, and when the call to **square** occurs, the expression **2*pi*r** is evaluated first. Its value is assigned to a temporary variable, which is passed as the parameter to square. Inside the function, this parameter is named **x**, and the function calculates x squared and returns it as a value. It is as if the following code executes:

```
pi = 3.14159
r = 2.54
# call square(2*pi*r)
parameter1 = 2*pi*r    # set the parameter value
x = parameter1         # First parameter is named x
                       # inside SQUARE
returnvalue = x*x      # Code within SQUARE, return x*x
c = returnvalue        # assign result of function call to c
print ("Circumference is ", c)
```

This is not how a function is implemented, but shows how the parameter is effectively passed; a copy is made of the parameters and those are passed. If the expression **2*pi*r** was changed to a simple variable, then the internal location of that variable would be passed.

Passing more structured objects works the same way, but they can behave differently. If a list is passed to a function, then the list itself cannot be modified, but the contents of the list can be. The list is assigned another name, but it is the same list. To be clear, consider a simple function that edits a list by adding a new element to the end:

```
def addend  (arg):
    arg.append("End")

z = ["Start", "Add", "Multiply"]
print (1, z)
addend(z)
print (1, z)
```

The list associated with the variable z is changed by this function call. It now ends with the string "End." The output from this is

```
1 ['Start', 'Add', 'Multiply']
2 ['Start', 'Add', 'Multiply', 'End']
```

This is the resulting output because the name **z** refers to a thing that consists of many other parts. The name **z** is used to access them, and the function cannot modify the value of z itself. It *can* modify what **z** indicates; that is, the components. Think of it, if it makes it simpler, as a level of indirection. A book can be exchanged between two people. The receiver writes a not in it and gives it back. It's the same book, but the contents are now different.

A small modification to **addend()** illustrates some confusing behavior. Instead of using **append** to add "End" to the list, use the concatenation operator, +:

```
def addend (arg):
    arg = arg + ["End"]

z = ["Start", "Add", "Multiply"]
print (1, z)
addend(z)
print (2, z)
```

The output is as follows:

```
1 ['Start', 'Add', 'Multiply']
2 ['Start', 'Add', 'Multiply']
```

The component "End" is not a part of the list **z** anymore. It was made a component inside of the function, but it's not present after the function returns. This is because the statement

```
arg = arg + ["End"]
```

creates a new list with "End" as the final component, and then assigns that new list as a value to **arg**. This represents an attempt to change the value that was passed, which cannot happen: changing the value of **arg** will not change the value of the passed variable **z**. Within the function **arg**, there is a new list with "End" as the final component. Outside, the list **z** has not changed.

The way that Python passes parameters is the subject of a lot of discussion on Internet blogs and lists. There are many names given for the method used, and while the technique is understood, it does differ from the way parameters are passed in other languages and is confusing to people who learned another language like Java or C before Python. It is important to remember that the actual value of an *object reference* being passed cannot be assigned a new value inside the function, but the things that it *references* or *points to* can be modified.

Multiple parameters are passed by position; the first parameter passed is given to the first one listed in the function declaration, the second one passed to given to the second one listed in the declaration, and so on. They are all passed in the same manner: as object references.

4.2.3 Default Parameters

It is possible to specify a value for a parameter in the instance that it is not given one by the caller. That may not seem to make sense, but the implication is that it will sometimes be passed explicitly and sometimes not. When debugging code it is common to embed **print** statements in specific places to show that the program has reached that point. Sometimes it is important to print out a variable or value there, other times, it is just to show that the program got to that statement safely. Consider a function named **gothere**:

```
def gothere (count, value):
    print ("Got Here: ",count, " value is ", value)
```

then throughout the program, calls to **gothere** would be sprinkled with a different value for **count** every time; the value of **count** indicates the statement that has been reached. This is a way of *instrumenting* the program, and can be very useful for finding errors. The code being debugged may look like the following:

```
year = 2015          # The code below is not especially
                     # meaningful
a = year % 19        # and is an example only.
gothere(1, 0)
b = year // 100
c = year % 100
gothere (2, 0)
d = (19 * a + b - b // 4 - ((b - (b + 8) // 25 + 1)
     // 3) + 15) % 30
e = (32 + 2 * (b % 4) + 2 * (c // 4) - d - (c % 4)) % 7
f = d + e - 7 * ((a + 11 * d + 22 * e) // 451) + 114
gothere (3, f)
month = f // 31
day = f % 31 + 1
gothere(4, day)
return date(year, month, day)
```

The output is as follows:

Got Here: 1 value is 0

Got Here: 2 value is 0

Got Here: 3 value is 128

Got Here: 4 value is 5

2015 4 5

The program reaches each of the four checkpoints and prints a proper message. The first two calls to **gothere** did not need to print a value, only the count number. The second parameter could be given a default value, perhaps **None**, and then it would not have to be passed. The definition of the function would now be as follows:

```
def gothere (count, value=None):
    if value:
        print ("Got Here: ",count, " value is ", value)
    else:
        print (Got Here: ", count)
```

The output this time is

Got Here: 1

Got Here: 2

Got Here: 3 value is 128

Got Here: 4 value is 5

2015 4 5

The assignment within the parameter list gives the name value a special property. It has a *default value*. If the parameter is not passed, then it takes that value; otherwise it behaves normally. This also means that **gothere** can be called with one or two parameters, which can be very handy. It is important to note that the parameters that are given a default value must be defined after the ones that are not. That's because otherwise it would not be clear what was being passed. Consider the (illegal) definition:

```
def wrong (a=1, b, c=12):
…
```

Now call **wrong** with two parameters:

```
wrong (2,5)
```

What parameters are being passed? Are they **a** and **b**? Are they **a** and **c**? It is impossible to tell. A legal definition would be

```
def right (b, a=1, c=12)
```

This function can be called as

```
right (19)
```

in which case b=19, a=1, and c=12. It can be called as

```
right (19, 20)
```

in which case b=19, a=19, and c=12. It can be called as

```
right (19, 19, 19)
```

in which case b=19, a=19, and c=19. But how can it be called passing **b** and **c** but not **a**?

```
right (19, c=19)
```

In this case, **a** has been allowed to default. The only way to pass **c** without also passing **a** is to give its name explicitly so that the call is not ambiguous.

4.2.4 None

Mistakes happen when writing code. They are unavoidable, and much time is spent getting rid of them. One common kind of mistake is to forget to assign a return value when one is needed. This is especially likely when there are multiple points in the function where a return can occur. In many programming languages, this will be caught as an error, but in Python it is not. Instead, a function that is not explicitly assigned a return value will return a special value called **None**.

None has its own type (*NoneType*), and is used to indicate something that has no defined value or the absence of a value. It can be explicitly assigned to variables, printed, returned from a function, and tested. Testing for this value can be done using the following:

```
if x == None:
```

or with

```
if x is None:
```

4.2.5 Example: The Game of Sticks

This is a relatively simple combinatorial game that involves removing sticks or chips from a pile. There are two players, and the game begins with a pile of 21 sticks. The first player begins by removing 1, 2, or 3 sticks from the pile. Then the next player removes some sticks, again 1, 2, or 3 of them. Players alternate in this way. The player who removes the last stick wins the game; in other words, if you can't move, you lose.

Functions are useful in the implementation of this game because both players do similar things. The action connected with making a move, displaying the current position, and so on are the same for the human player and the computer opponent. The current status or state of the game is simply a number, the number of sticks remaining in the pile. When that number is zero, then the game is over, and the loser is whichever player is supposed to move next. The code for a pair of moves, one from the human and one from the computer, might be coded in Python as follows:

```
displayState(val)                # Show the game board
userMove = getMove()             # Ask user for their move
val = val – userMove             # Make the move
print ("You took ", userMove, " sticks leaving ", val)
if gameOver(val):
    print("You win!")
else:
    move = makeComputerMove (val) # Calculate the
                                  # computer's move
    print ("Computer took ", move, " sticks leaving ", val)
    if gameOver(val):
        print("Computer wins!")
```

The current state of the game is displayed first, and then the human player is asked for their move. The move is simply the number of sticks to remove. When the move has been made, if there are no sticks left, then the human wins. Otherwise, the computer calculates and makes a move; again, if no sticks remain then the game is over, in this case the computer being the winner. This entire section of code needs to be repeated until the game is over, of course.

There are four functions that must be written for this version: **displayState()**, **getMove()**, **gameOver()**, and **makeComputerMove()**.

The function **displayState()** prints the current situation in the game. Specifically, it prints one "O" character for each stick still in the pile, and does so in rows of 6. At the beginning of the game, this function would print the following:

```
O O O O O O
O O O O O O
O O O O O O
O O O
```

which is 21 sticks. The code is as follows:

```
def displayState(val):
    k = val        # K represents the number of
                   # sticks not printed
    while k > 0:   # So long as some are not printed …
        if k >=6: # If there is a whole row, print it.
            print ("O O O O O O ", end="")
            k = k - 6  # Six fewer sticks are unprinted
        else:
            for j in range(0,k):  # Print the remainder
                print ("O ", end="")
            k = 0                 # None remain
        print ("")
```

Note that the function is named for what it does. It does only one thing, it modifies no values outside of the function, and it serves a purpose that is needed multiple times. These are all good properties of a function.

The function **getMove()** prints a prompt to the user/player asking for the number of sticks they wish to remove and reads that value from the keyboard, returning it as the function value. Again, this function is named for what it does and performs a single, simple task. One possibility for the code is as follows:

```
def getMove ():
     n = int(input ("Your move: Take away how many?  "))
     while n<=0 or n>3:
        print ("Sorry, you must take 1, 2, or 3 sticks.")
        n = int(input ("Your move: Take away how many?  "))
     return n
```

The function **gameOver()** is trivial, but lends structure to the program. All it does is test whether the value of **val**, the game state variable, is zero. There may be other end-of-game indicators that could be tested here.

```
def gameOver (state):
    if state == 0:
        return True
    return False
```

Finally, the most complicated function, **getComputerMove()**, can be attempted. Naturally, a good game presents a challenge to the player, and so the computer should win the game it if can. It should not play randomly if that is possible. In the case of this particular game, the winning strategy is easy to code. The player to make the final move wins, so if there are 1, 2, or 3 sticks left at the end, the computer would take them all and win. Forcing the human player to have 4 sticks makes this happen. The same is true if the computer can give the human player (i.e., leave the game in the state of having 8, 12, or 16 sticks). If the human moves first (as it does in this implementation), the computer tries to leave the game in a state where there are 16, 12, 8, or 4 sticks left after its move. The code could be written as follows:

```
def getComputerMove (val):
    n = val % 4
    if n<=0:
        return 1
    else:
        return n
```

There some of the details needed to finish this game properly are left as an exercise.

4.2.6 Scope

A variable that is defined (first used) in the main program is called a *global* variable and can be accessed by all functions if they ask for it. A variable that is used in a function can be accessed by that function and is not available in the main program. It's called a *local* variable. This scheme is called *scoping*: the locations in a program where a variable can be accessed is called its *scope*. It's is easy to understand unless a global variable has the same name as a local one, in which case the question is: "what value is represented by this name?" If a variable named "x" is global and a function also declares a variable having the same name, this is called *aliasing*, and it can be a problem.

In Python, a variable is assumed to be local unless the programmer specifically says it is global. This is done in a statement. For example,

```
global a, b, c
```

tells Python that the variables named **a**, **b**, and **c** are global variables, and are defined outside of the function. This means that after the function has completed execution, those variables can still be accessed by the main program and by any other functions that declare them to be global.

Global variables are thought by some programmers to be a bad thing, but in fact they can be quite useful and can assist in the generality of the functions that are a part of the program. A global variable should represent something that is known to the whole program. For instance, if the program is one that plays checkers or chess, then the board can be global. There is only one board, and it is essential to the whole program. The same applies to any program that has a central set of data that many of the functions need to modify.

An example of central data is the game state in a video game. In the Sticks game program, the function **getComputerMove**() takes a parameter – the game state. There is only one game state, and although for some games it can involve many values, in this case, there is only one value: the number of sticks remaining. The function can be re-written to use the game state variable **val** as a global in the following way:

```
def getComputerMove ():
    global val
    n = val % 4
    if n<=0:
        return 1
    else:
        return n
```

Similarly, the function that determines whether the game is over could use **val** as a global variable. It would be poor stylistic form to have **getMove**() use a global variable for the user's move. The name does imply that the function will get a move, and so that value should be returned as an explicit function return value.

If a variable is named as global, then that name cannot be used in the function as a local variable, as well. It would be impossible to access it, and it would be confusing. It is a common programming error to forget to declare a variable as global. When this happens, the variable is a new one local to the function, and starts out with a value of 0. Thus, no syntax error is detected, but the calculation will almost certainly be incorrect. It is a good idea to identify global variables in their names. For example, place the string "_g" at the end of the names of all global variables. The game state above would be named **val_g**, for example. This would be a reminder to declare them properly within functions.

Other kinds of data that could be kept globally would include lists of names, environment or configuration variables, complex data structures that represent a single underlying process, and other programming objects that are referred to as *singletons* in software engineering. In Python, because they have to be explicitly named in a declaration there is a constant reminder of the variable's scope.

4.2.7 Variable Parameter Lists

The **print()** function is interesting because it seems to be able to accept any number of parameters and deal with them. The statement

```
print(i)
```

prints the value of the variable **i**, and

```
print (i,j,k)
```

prints the value of all three variables **i**, **j**, and **k**. Is this some sort of special thing reserved for **print()** because Python knows about it? No. Any function can do this. Consider a function,

```
fprint ( "format string", variable list)
```

where the format string can contain the characters "f" or "i" in any combination. Each instance of a letter should correspond to a variable passed to the function in the variable list, and it will be printed as a floating point if the corresponding character in the format string is "f" and as an integer if it is "i." The call

```
fprint("fi", 12, 13)
```

prints the values 12 and 13 as a float and an integer, respectively. How can this be written as a Python function?

The function starts with the following definition:

```
def fprint (fstring, *vlist)
```

The expression ***vlist** represents a set of positional parameters, any number of them. This is preceded by a specific parameter **fstring**, which is the format string. A simple test of this would be to just print the variables in the list to see if it works:

```
def fprint (fstring, *vlist)
    for v in vlist:
        print v
```

When called as fprint(“”, 12, 13, 14,15), this prints

```
12
13
14
15
```

The list of variables after the * character is turned into a tuple, which is passed as the parameter, so the ***vlist** counts as a single parameter with many components.

To finish the original function, we have to remove characters from the front of the format string, match them against a variable, and print the result as the format character dictates. We need the same loop as above, but we also need an index for the format string that increases each time through and is used to indicate the format. It is also important that the number of format items equals the number of variables:

```
def fprint (s, *vlist):
    i = 0
    if len(s) != len(vlist):    # Format string and variable
                                # list agree?
        print ("There must be the same number of variables
               as format items.")
        return
for v in vlist:                 # For each variable
      if s[i] == "f":           # Is the corresponding
                                # format 'f'?
         fv = float(v)          # Yes. Make it a float
         print (fv, " ", end="")   # … and print it
      elif s[i] == "i":            # Is the corresponding
                                   # format 'i'?
           iv = int(v)             # Yes. Make it an
                                   # integer
```

```
        print(iv, " ", end="")  # … and print it
    else:
        print ("?", end="")     # Don't know what this
                                # is. Print it
      i = i + 1
```

All of the known positional parameters must come before the variable list; otherwise the end of the variable list cannot be determined. There is a second complication, that being the existence of *named* parameters. Those are indicated by a parameter such as **nlist. The two * characters indicate a list of named variables.

4.2.8 Variables as Functions

Because Python is effectively untyped and variables can represent any kind of thing at all, a variable can be made to refer to a function; not the function name itself, which always refers to a specific function, but a variable that can be made to refer to *any* function. Consider the following functions, each of which does one trivial thing:

```
def print0():
    print ("Zero")
def print1():
    print ("One")
def print2():
    print ("Two")
def print3():
    print("Three")
```

Now make a variable reference one of these functions by means of an assignment statement:

```
printNum = print1    # Note that there is no parameter
                     # list given
```

The variable **printNum** now represents a function, and when invoked, the function it represents will be invoked. So

```
printNum()
```

will result in the output

```
One
```

Why did the statement `printNum = print1` not result in the function print1 being called? Because the parameter list was absent. The statement

```
printNum = print1()
```

results in a call to print1 at that moment, and the value of the variable printNum is the return value of the function. This is the essential syntactic difference: print1 is a function value, and print1() is a call to the function. To emphasize this point, here is some code that allows the English name of a number between 1 and 3 to be printed:

```
if a == 1:
      printNum = print1  # Assign the function print1
                         # to printNum
elif a == 2:
      printNum = print2  # Assign the function print2
                         # to printNum
else:
      printNum = print3  # Assign the function print3
                         # to printNum
      . . .
printNum()               # Call the function represented
                         # by printNum
```

There are more subtle uses in this case. Consider this use of a list

```
a = 1
printList = [print0, print1, print2, print3]
printNum = printList[a]
printNum()
```

that results in the output

```
One
```

The final iteration of this is call the function directly from the list:

```
printList[1]()
```

This works because printList[1] is a function, and a function call is a function followed by (). This is overly complicated, and so it is rarely used.

For those with an interest or need for mathematics, consider a function that computes the derivative or integral of another function. Passing the function to be differentiated or integrated as a parameter may be the best way to proceed in these cases.

Example: Find the maximum value of a function

Maximizing a function can have important consequences in real life. The function may represent how much money will be made by manufacturing various objects, how many patients can get through an emergency ward in an hour, or how much food will be grown with particular crops. If the function is easy to use, then there are many mathematically sound ways to find a maximum or minimum value, but if a function is hard to work with, then less analytical methods may have to be used. This problem proposes a search for the best pair of parameters to a problem that could be solved using a method called *linear programming*.

The problem goes like this:

> A calculator company produces a scientific calculator and a graphing calculator. Long-term projections indicate an expected demand of at least 100 scientific and 80 graphing calculators each day. Because of the limitations on the production capacity, no more than 200 scientific and 170 graphing calculators can be made daily. To satisfy a shipping contract, a total of at least 200 calculators much be shipped each day. If each scientific calculator sold results in a $2 loss, but each graphing calculator produces a $5 profit, how many of each type should be made daily to maximize net profits?

Let **s** be the number of scientific calculators manufactured and **g** be the number of graphing calculators. From the problem statement,

100 <= s <= 200

80 <= g <= 170

Also,

s + g > 200,   or   g > 200 - s

Finally, the profit, which is to be maximized, is as follows:

$P = -2s + 5g$

First, code the profit as a function:

```
def profit (s, g):
    return -2*s + 5*g
```

A search through the range of possibilities will run through all possible values of s and all possible values of g; that is, s from 100 to 200 and g from 80 to 170. The function is evaluated at each point and the maximum is remembered:

```
# Range for s is x0 .. x1
# Range for g is y0 .. y1
# s+g must be >= sum
def searchmax (f, x0, y0, x1, y1, sum):
    pmax = -1.0e12
    ps = -100
    pg = -100
    for s in range (x0, x1+1):        # For all possible s
        for g in range (y0, y1+1):    # For all possible g
            if s+g >= sum:            # Condition is ok?
                p = f (s, g)          # Calculate the
                                      # profit.
                if p>=pmax:           # Best so far?
                    pmax = p          # Yes.
                    ps = s            # Save it and
                    pg = g            # the parameters
    return ( (ps, pg) )
```

Finally, the call that does the optimization calls the search function, passing the profit function as a parameter:

```
c = searchmax (profit, 100, 80, 200, 170, 200)
print (c)
```

The answer found is the tuple (100, 170), or s=100 and g = 170, which agrees with the correct answer as found by other methods. This is only one example of the value of being able to pass functions as parameters. Most of the code that does this is mathematical, but may accomplish practical tasks like optimizing performance, drawing graphs and charts, and simulating real world events.

4.2.9 Functions as Return Values

Just as any value, including a function, can be stored in a variable, any value, including a function, can be returned by a function. If a function that prints the English name of a number is desired, it could be returned by a function:

```
def print0():
    print ("Zero")
def print1():
```

```
    print ("One")
def print2():
    print ("Two")
def print3():
    print("Three")

def getPrintFun (a):        # Return a function to print a
                            # numeric value 0..3
  if a == 0:
     return print0          # Return the function print0
                            # as the result
  elif a == 1:
     return print1          # Return the function print1
                            # as the result
  elif a == 2:
     return print2          # Return the function print2
                            # as the result
  else:
     return print3          # Return the function print3
                            # as the result
```

Calling this function and assigning it to a variable means returning a function that can print a numerical value:

```
printNum = getPrintFun(2) # Assign a function to printNum
```

and then

```
printNum()    # Call the function represented by printNum
```

results in the output

```
Two
```

The function **printFun** returns, as a value, the function to be called to print that particular number. Returning the name of the function returns something that can be called.

Why would any of these seeming odd aspects of Python be useful? Allowing a general case, permitting the most liberal interpretation of the language, would permit unanticipated applications, of course. The ability to use a function as a variable value and a return result are a natural consequence of Python having no specific type connected with a variable at compilation time. There are many specific reasons to use functions in this way. Imagine a function that plots a graph.

Being able to pass this function another function to be plotted is surely the most general way to accomplish its task.

4.3 RECURSION

Recursion refers to a way of defining things and a programming technique, not a language feature. Something that is recursive is defined at least partly in terms of itself. This seems impossible at first, but consider the case of a grocery list (not a Python *list*) of items:

milk, bread, coffee, sugar, peanut butter, cheese, jam

Each element in the list can be called an *item*, and represents something to be purchased at a grocery store. The smallest list is one having only a single element:

milk

Thus, a list can be simply an item. What else can it be? It appears to be several items separated by commas. One way to describe this is to say it can be an *item followed by a comma followed by a list*. The complete definition is, presuming that the symbol -> means "can be defined as," is as follows:

list -> item # **list** can be defined as an item

list -> item, list # **list** can be defined as an item, a comma, and a list

In this way the list **milk** is defined as a list by the first rule. The list **milk, bread** is a list because it is an item (**milk**) followed by a comma followed by a list (**bread**). It is plain that a list is defined here in terms of itself, or at least in terms of a previous partial definition of itself.

When talking about functions, a function is recursive if it contains within it a call to itself. This is normally done only when the thing that it is attempting to accomplish has a definition that is recursive. Recursion as a programming technique is an attempt to make the solution simpler. If it does not, then it is inappropriate to use recursion. A problem some beginning programmers have with the ideas of a recursive function is that it appears that it does not terminate. Of course, it is essential that a function does return, and a program that never ends is almost always in error. The problem really is how to make certain that a chain of function calls terminates eventually.

The following function will never return once called:

```
def recur1 (i)
   recur1(i+1)
   print (i)
```

It will not result in any output, either. Why not? Because the first thing it does is call itself, and always does so. When it does, the next thing is does is call itself again, and then again, and so on. The following function, on the other hand, does terminate:

```
def recur2 (i)
   if i>0:
          recur2(i-1)
   print (i)
```

When called, it checks its parameter **i**. If that parameter is greater than zero, then it calls itself with a smaller value of **i**, meaning that eventually **i** will become smaller than 0 and the chain of calls will stop. What will be printed? The first call to **recur2** that does not end up calling itself is when i==0, so the first thing printed is 0. Then the function returns to the previous recursive call, which had to be where i == 1. The second thing printed will be 1, and so on, until it returns to the original call to the function with the original value of **i**, at which point it prints **i**. This is a trivial example of a recursive function, but it illustrates how to exit from the chain of calls: there must be a condition that defines the recursion. When that condition fails, the recursion ceases.

Each call to the function can be thought of as an instance of that function, and it will create all of the local variables that are declared within it. Each instance has its own copy of these, including its parameters, and each call returns to the caller as occurs with any other function call. When the recursive call to **recur2()** returns, the next thing to be done is (in this case) to print the parameter value. A call to **recur2()** passing the parameter 4 results in the following instances of that function being created:

```
recur2(4) i = 4   # This is the function state, with parameter i
                    given for this instance
  i>0 so call recur2(i-1) = recur2(3)        # This is the code
                                             # executed
    recur2(3) i = 3                          # State
    i>0 so call recur2(i-1) = recur2(2)      # Code executed
      recur2(2) i = 2                        # State
```

```
      i>0 so call recur2(i-1) = recur2(1)     # Code executed
        recur2(1) i = 1                       # State
        i>0 so call recur2(i-1) = recur2(0)   # Code executed
          recur2(0) i = 0                     # State
          i== 0 so recur2 is NOT called       # Code executed
          print(i) -> print(0)                # Code executed ,
                                              # prints 0
          return                              # Code executed
        print(i) -> print(1)                  # Code executed ,
                                              # prints  1
        return                                # Code executed
      print(i) -> print(2)                    # Code executed ,
                                              # prints   2
      return                                  # Code executed
    print(i) -> print(3)                      # Code executed ,
                                              # prints    3
    return                                    # Code executed
  print(i) -> print(4)                        # Code executed ,
                                              # prints     4
  return                                      # Code executed
```

By tracing through the statements that are executed in this way, it can be seen that the recursion does end, and the output or result can be verified.

One important use of recursion is in reducing a problem into smaller parts, each of which has a simpler solution than does the whole problem. An example of this is searching a list for an item. If **names = [Adams, Alira, Attenbourough, …]** is a Python list of names in alphabetical order, answer the question: "Does the name *Parker* appear in this list?" There is a built-in function that does this, but this example is a good teaching tool. The built-in function may also be slower than the solution that is devised here.

The function will return **True** or **False** when passed a list and a name. The obvious way to solve the problem is to iterate through the list, looking at all of the elements until the name being searched for is either found or it is not possible to find it any more (i.e., the current name in the list is larger than the target name). Another, less obvious way to conduct the search is to divide the list in half, and only search the half that has the target name in it. Consider the following names in the list:

… Broadbent   Butterworth Cait Cara Carling Devers Dillan Eberly Foxworthy …

The name in the middle if this list is *Carling*. If the name being searched for is lexicographically smaller than *Carling*, then it must appear in the first half; otherwise it must appear in the second half. That is, if it is there at all. A recursive example of an implementation of this is as follows:

```
# Search the list for the given name, recursively.
def searchr (name, nameList):
    n = len(nameList)         # How many elements in this
                              # list?
    m = n/2
    if name < nameList[m]:    # target name is in the first
                              # half
        return searchr (name, nameList[0:m])  # Search the
                                              # first half
    elif name > nameList[m]:  # target must be in the
                              # second half
        return searchr (name, nameList[m:n]  # Search the
                                             # second half
    else:
        return True
```

If the name is in the list, this works fine. One way to think of this is that the function **searchr()** takes a string and a list as parameters and finds the name in the list if it's there. The way it works is not clear from outside the function (without being able to see the source) and should not matter. If the target is to be found in the first half of the list, for example, then call **searchr()** with the first half of the list.

```
searchr (name, nameList[0:m])
```

The fact that the call is recursive is not really concerning. How can the problem of a name not being in the list be solved?

When the name is not in the list, the program will continue until there is but one item in the list. If that item is not the target, then it is not to be found. If n=1 (only one item in the list) and **nameList[0]** is not equal to the target, then the target is not found in the list and the return value is **False**. The final program is as follows:

```
def searchr (name, nameList):
    n = len(nameList)     # How many elements in this list?
    m = int(n/2)
```

```
    if n==1 and nameList[0]!=name:  # End of the recursive
                                    # calls
        return False                # It's not in this
                                    # list.
    if name < nameList[m]:    # target name is in the first
                              # half
        return searchr (name, nameList[0:m])  # Search the
                                              # first half
    elif name > nameList[m]:   # target must be in the
                               # second half
       return searchr (name, nameList[m:n])  # Search the
                                             # second half
    else:
        return True
```

Many algorithms have fundamentally recursive implementations, meaning that the effective solution in the code involves a recursive function call. Many standard examples in beginning programming are not properly implemented recursively. Commonly encountered samples with a recursive solution include the *factorial*, which has a recursive definition but is not best implemented that manner, and any other basically linear technique (linear search, counting, and min/max finding) that does not do a reasonable subdivision. Testing the first component, for example, and then recursively looking at the remaining elements is a poor way to use recursion. It would be much better to use a loop. Let's write an example: find the maximum value in a given list. The non-recursive method (reasonable) is as follows:

```
def max (myList):
    max = myList [0]
    for I in range(1, len(myList)):
        if myList[i] > max:
            max = myList[i]
    return max
```

This is an effective way to find the largest value in a list and is easily understood by a programmer reading the code. Here is a recursive solution:

```
def maxr (myList):
    m1 = myList[0]
    if len(myList)>1:
        m2 = maxr (myList[1:])
    else:
```

```
        return m1
    if m1 > m2:
        return m1
    else:
        return m2
```

This function works by subdividing the list into two parts, as is often done with a recursive solution. The idea is to compare the first element in the list with the maximum of the remainder of the list to see which is bigger. For this particular problem, this is not an obvious approach. It is less efficient and less obvious than the iterative version that preceded it. The use of recursion simplifies some problems, but it is not a universally applicable technique. Examples of useful recursive functions will be examined in later chapters.

4.3.1 Avoiding Infinite Recursion

There is a limit to how many times a function can call itself without returning, because each call uses up some amount of memory and memory is a finite resource. Usually, when this happens, a programming error has occurred and the function has slipped into an *infinite recursion*, in which it will continue to call itself without end. Recursion can be confusing to visualize and this sort of problem occurs frequently. How can it be avoided?

Programming the function correctly eliminates the problem, of course, but there are some basic rules that will avoid the problem at the early stages. Assuming that *global variables are* ***not*** *being referenced*:

1. A function that begins with a call to itself is always infinitely recursive. The first thing the function does is call itself, and no matter what the parameters are, it can never end.
2. Every recursive call within a function must have a condition upon which that call will be avoided. The function may return sometime before the call is made, or perhaps the call happens within an *if* statement, but there must be such a condition. If it exists, it is expressible as a Boolean expression, and this should be placed in a comment near the recursive call. The call is suspect until this happens.
3. Avoid passing a function to itself. The call to a parameter hides the fact that recursion is taking place.

4. It is possible to have a global variable that is a count of the depth of recursion. The function will increment this count whenever a recursive call is made and decrease it just before returning. If the count ever gets larger than a reasonable estimate of the maximum depth then the function could stop any more calls and back out, or an error message could be printed.

4.4 CREATING A PYTHON MODULE

In some of the examples given so far there is a statement at the beginning that looks like "import name." The implication is that there are some functions that are needed by the program that are provided elsewhere, possibly by the Python system itself or perhaps by some other software developer. The idea of writing functions that can be re-used in a straightforward way is very important to the software development process. It means that no programmer is really alone; that code is available for doing things like generating random numbers or interfacing with the operating system or the Internet, and that it does not to be created each time. In addition, there is an assumption that a module *works correctly*. When a programmer builds a collection of code for their own use, it needs to be tested as thoroughly as possible, and from that time on it can be used in a package with confidence. If a program has errors in it, then look in the code for that program first and not in the modules. This makes debugging code faster.

What is a module? It is simply a function or collection of functions that reside in a file whose name ends in .py. Technically, all of the code developed so far qualifies as modules. Consider as an example the function from the previous section that finds the maximum value in a list. Save the functions **max()** and **maxr()** in a file named ***max.py***. Now create a new Python program named ***usemax.py*** and place it in the same directory as ***max.py***. If the two files are in the same directory then they can "see" each other in some sense.

Here is some code to place in the file ***usemax.py***:

```
import max
d = [12,32,76,45,9,26,84,25,61, 66, 1,2]
print ""MAX is"", max.max(d),"" MAXR is"", max.maxr(d))
if max.maxr(d) != max.max(d):
    print ""*** NOT EQUAL ***"")
```

This program is just a test of the two functions to make certain that they return the same value for the same list, the variable **d**. Note two things:

1. The statement **import max** occurs at the beginning of the program, meaning that the code inside this file is available to this program. Python looks inside this file for the function and variable names.
2. When the function **max()** or **maxr()** is called, the function name is preceded by the module name (**max**) and a period. This syntax informs the Python system that the name **maxr()** (for example) is found in the module **max** and not elsewhere.

The first time that the module is loaded into the Python program, the code in the module is executed. This allows any variable initializations to be performed. Henceforth, that code is not executed again, and functions within the module can be called knowing that the initializations have been performed.

The module could reside in the same directory as the program that uses it, but does not have to. The Python system recognizes a set of directories and paths and modules can be placed in some of those locations as well, making it easier for other programs on the same computer to take advantage of them. On the computer used to create the examples in this book, the directory C:\Python34\Lib can be used to store modules, and they will be recognized by **import** statements.

Finally, if the syntax **max.maxr(list)** seems a bit cumbersome, then it is possible to import specific names from the module into the program. Consider the following rewrite of **usemax.py**:

```
from max import max, maxr
d = [12,32,76,45,9,26,84,25,61, 66, 1,2]
print ("MAX is ", max(d), " MAXR is ", maxr(d))
if maxr(d) != max(d):
    print ("*** NOT EQUAL ****")
```

The statement **from max import max, maxr** instructs Python to recognize the names **max** and **maxr** as belonging to the module named max (i.e., as residing in the file named ***max.py***). In that case, the function can be called by simply referencing its name.

There appears to be a name conflict with the package named **max** and the function named **max**, but in fact, there is no problem. It is not uncommon to find this sort of naming relationship (example: **random.random()**). The module name

max refers to a file name, ***max.py***. The function name **max** refers to a function within that file.

4.5 PROGRAM DESIGN USING FUNCTIONS–THE GAME OF NIM

Nim is a game so old that its origins have been lost. It was likely invented in China, and it is one of the oldest games known. It was also one of the first games to have a computer or electronic implementation and has been the frequent subject of assignments in computer programming classes. This program will implement the game and play one side. The code serves as an example of how to design a computer program using functions and modularity - it is an example of a *top-down* design.

The game starts with three rows of objects, such as sticks or coins, and there are a different number of objects in each row. In this version, there are 9, 7, and 5 sticks, which are represented by the | character. A player may remove as many objects from one row as they choose, but they must remove at least one and must take them only from one row. Players take turns removing objects, and the player taking the final one is the winner.

Playing this game involves asking the user for two numbers: the row from which to remove sticks, and how many to remove. The human player is prompted for the row, then the number. Then the computer removes some sticks (take its turn) and prints the new state.

A list named **val** contains the number of sticks in each row. Initially,

```
val = [5, 7, 9]
```

This is the game state, and is critical to the game as it defines what moves are possible. Also, when the state is [0,0,0] then the game is over.

When the user choses to remove N sticks from row M, the action is

```
val[M] = val[M] - N
```

Of course, **N** and **M** must be tested to make certain that **M** is between 0 and 2, and M is as large as **val[M]**. M defines the row chosen to remove sticks from, and N is the number of sticks to remove. A move can therefore be defined as a list **[row, sticks]**.

A program that uses functions should be built from the highest level of abstraction downwards. That is, the main program should be developed first, and should be expressed in terms of functions that do logical things, but that may not be designed or coded yet. The main program could look something like this:

```
val = [5, 7, 9]      # the game state: 5, 7, and 9 sticks
done = False         # Is the game over?
userMove = [-1, -1] # A move is a row and a number of
                     # sticks.
print ("The game of Nim.")
rules()                    # Print the rules for the game
while not done:            # Run until the game is over
    displayState(val)      # Show the game board
    prompt(userMove)       # Ask user for their move
    ok = legalMove (userMove, val)  # Was the player's move
                                    # OK?
    while not ok:
        print ("This move is not legal.")
        displayState(val)
        prompt(userMove)      # Ask user for their move
        ok = legalMove (userMove, val)
    makeMove (userMove)       # Make it
    if gameOver(val):
        print("You win!")
        break;
    print ("State after your move is ")  # display it.
    displayState(val)
```

This program is built using components (modules) that are not written yet, but that have a purpose that is defined by what the program needs. Those modules/functions are as follows:

rules()	- Print out the rules of the game.
displayState(v)	- Print the game state (how many sticks in each row).
prompt()	- Ask the user for their move.
legalMove(r, n)	- Is the move legal?
makeMove(r, n)	- Make this move.

Using functions, the first thing that is needed is to display the game state. The program prints the number of sticks in each of the three rows, and does so in a graphical way, rather than just displaying the numbers on a console. Given the situation as described so far, the non-trivial function is **displayState()**, which prints the current state of the game – how many sticks in each row. It will be passed a list representing the current state.

```
def displayState(val):                 # val is the list with
                                       # the state
    for j in range(0,3):               # there are 3 rows;
                                       # print each one
        print (j+1, ": ", end="")      # Print the row number
        for i in range(0,val[j]):      # val[j] is the
                                       # current row
            print ("| ",end="")        # print a '|' for each
                                       # stick
        print("")                      # print an end of line
```

When called at the beginning of the game, here's what the result of a call to this function would be:

```
1 : | | | | |
2 : | | | | | | |
3 : | | | | | | | | |
```

This function does a single task, uses a parameter to guide it and make it more general, and is named for what it does. These are signs of a good function. Note that the first row is labeled "1," but it is element 0 of the list. It is common in user interfaces to adapt to the standard human numbering scheme that begins with 1 instead of 0. When the user enters a row number, care must be taken to subtract 1 from it before using it as an index.

There is no required order for writing these functions, but the next one used in the program is **prompt()**. This asks the user to input a row and then reads a row number, then prompts the user to enter a number of sticks to remove and then reads that value, too. The two numbers are placed into a list that was passed so that the values can be returned to the caller.

```
def prompt (move):
  row =    input ("Your move: which row? ")  # Prompt for row &
                                             # read it
  sticks = input ("          how many sticks?") # Prompt for
                                                # sticks & read
# Convert row to integer and decrement to be from 0 to 2.
  move[0] = int(row)-1                     # Assign to the list[0]
  move[1] = int(sticks)                    # Assign value to list[1]
```

This function again does a simple task, uses a parameter, and is named appropriately.

Next is the question "Is this move legal?" A move is legal if the row is between 0 and 2 inclusive, and if the number of sticks in that row is greater than or equal to the number of sticks to be removed. The function returns **True** or **False**.

```
def legalMove(move, state):
    row = move[0]                  # Which row was requested?
    sticks = move[1]               # How many sticks
    if row<0 or row>2:             # Legal number of rows?
        return False               # No
    if sticks<=0 or sticks>val[row]:  # Legal number of
                                      # sticks?
        return False                  # No
    return True                    # Both were ok, so the
                                   # move is OK.
```

Making a move involves decreasing the specified row by the specified number of sticks. This could have been done in **legalMove()** if it was acceptable to do multiple things in a function. Eventually, that will be necessary, but for now, a new function will be written, named **makeMove()**, that implements a specified play in the game.

```
def makeMove(move, state):
    row = move[0]                  # Subtract move[1] sticks from
    sticks = move[1]               # those that are in row
                                   # move[0].
# Place the new number of sticks in the state list
    state[row] = state[row]-sticks
```

There is a strategy that permits a player to always win. It involves computing what amounts to a *parity* value and making a move to ensure that parity is maintained. Consider the initial state and the state after taking two sticks from row 1:

Row 1 = 5 =	0 1 0 1	row 1 = 3 =	0 0 1 1
Row 2 = 7 =	0 1 1 1	row 2 = 7 =	0 1 1 1
Row 3 = 9 =	1 0 0 1	row 3 = 9 =	1 0 0 1
Parity	1 0 1 1		1 1 0 1

The parity is determined by looking at each digit in the binary representation of the values. In each column (digit position), the parity bit for that column is 1 if the number of 1 bit in the column is odd and 0 if it is even. This can be calculated using the exclusive-OR operator, which is ^. The strategy in Nim is to make a move that makes the parity value 0. This is always possible if parity is not 0; in the situation above, the computer might remove 5 sticks from row 3 giving the following state:

row 1 = 3 = 0 0 1 1

row 2 = 7 = 0 1 1 1

row 3 = 4 = 0 1 0 0

Parity 0 0 0 0

This is what the sketch does after every move the player makes: it makes all possible moves, computing the parity after each one. When the one with zero parity is found, it makes that move. The function **eval()** calculates the current parity value as **val[0]^val[1]^val[2]**.

NOTE *The computer always wins because the user always makes the first move. Alternating who moves first would make the gameplay fairer.*

4.5.1 The Development Process Exposed

In the introduction to the Nim program, we said that this was an example of *top-down* design. This means that the larger program, or the main program, is designed first. The question should *be what are the steps involved in solving this problem*? The answer to that question is written down in terms of functions that have not been written yet, but that have a known and required purpose within the solution. In the Nim game, it is known that the user's move will have to be read from the keyboard and that the current state of the game will have to be displayed, so those two functions can be presumed to be important to the solution when sketching the main program.

Once the high-level part of the program has been devised, it can be typed in and tested. The functions that are needed but are not yet written can be coded as *stubs*: functions that do not implement their task but that are present and prevent syntax errors. The first try at a solution of this sort does not solve the problem, but is simply a step towards the solution. In the case of Nim, the very first step could be written as follows:

```
Repeat
  Display the game
  Ask user for their move
  Make user's move
  Generate computer's move
  Make computer's move
Until someone wins
Display the winner
```

None of these steps are written as proper Python code, but that is acceptable for a first step. Translating this into Python comes next.

```
Done = false
while not done:                # Run until the game is over
      displayState()           # Show the game board
      prompt()                 # Ask user for their move
      makeMove ()              # Make it
      if not gameOver():       # Computer move?
            makeComputerMove()# Determine computer's move
      done = gameOver()        # Is the game over?
printWinner()
```

At this point in the design, neither the data structures nor algorithms used in the solution have been devised. This is merely a sequence of steps that could lead to a program that works. The functions can now be written as stubs:

```
def displayState():            def prompt():
    print("Display state")         print("Enter move")

def makeMove():                def gameOver():
    print ("Make move")            if random.random()<0.2:
                                       return False
                                   return True


def makeComputerMove():        def printWinner():
    print ("compute a move")       print("The winner is:")
```

The output from this program might be as follows:

```
Display state
Enter move
Make move
Display state
Enter move
```

```
Make move
compute a move
The winner is:
```

The exact output will be random, depending on what the return value of **gameOver()** is. This code can be thought of as one *iteration* of the solution or as a *prototype*. The next step is to refine the solution by implementing one of the stubs. Each time that happens, a set of decisions is made concerning the nature of the data structures used to implement the solution: the use of a list for the game state, for instance. Three integers could have been used instead, but once the decision is made about the approach, it should be used consistently unless it becomes infeasible.

Repeatedly implementing the stubs creates new prototypes, each one more functional than the one before. Some of the functions may require an application of this same process. Complex functions can be coded in terms of other stubs, and so on. The simpler functions, such as those that calculate based only on their parameter, should be completed first and should not involve permanent design choices.

A programming process of this kind can be thought of as *iterative refinement*. After the first step, a complete program that compiles and runs should be refined. This can be very useful, especially when dealing with graphical user interfaces and games. The interface might well be complete before any real functionality is present, and this permits a demonstration of the concept before the program is done.

4.6 SUMMARY

Python allows a programmer to create a function that does something new. A function is code that has a name and can be executed simply by invoking that name. It usually represents some task that has to be done frequently. A function should also have one main task and that task should be represented in the function name (for example, *maximum*, *square*, or *search*). Many functions return a value, and finding that value is frequently the purpose of the function (e.g., *sine* or *cosine*).

The name of a function can be used to call that function, but it can also be assigned to a variable, passed as a parameter to another function, or returned as a value. A function can have variables that belong to it; they are called local variables and vanish after the function returns. They can also use variables defined outside of the function if they appear in a *global* statement.

A special value named **None** is used to represent *no value*, and it is returned by a function that does not explicitly return some other value. A *module* is a function or collection of functions that reside in a file whose name ends in .py.

The use of functions can organize a computer program in a logical way. A program can be defined in terms of functions that are desired but not yet written, and then those functions can be defined as code or in terms of other functions. Functions are often named but are incomplete, and are called *stubs* – they permit the program to be compiled while still under development.

A function that calls itself is said to be *recursive*. Such functions can be very valuable in simplifying the code for some algorithms, especially ones in which some thing is actually defined in terms of itself, but care must be taken when programming to ensure that a recursive function always ultimately returns.

Exercises

1. Write a Python function that takes a tuple of numbers as a parameter and returns the location (index) of the maximum value found in that tuple.
2. Word processing systems sometimes need to shorten a word to make it fit on a line. Write a function that takes a string containing a single word and decides where to hyphenate it. A hyphen can occur before the endings -ing, -ed, -ate, -tion, or -ment. It could also occur after a prefix: pre-, post-, para-, pro-, con-, or com-. Otherwise, place a hyphen somewhere in the middle of the word. The function should return a tuple containing the first and second half of the word split at the hyphen.
3. Pascal's triangle is an arrangement of numbers in rows and columns such that each number in a row is the sum of the two numbers above it. An example is as follows:

```
      1
    1   1
  1   2   1
1   3   3   1
```

Write a function **triangle(n)** that prints the first n rows of such a triangle. Extra marks will be given for proper indentation so it looks like a triangle.

4. Write a function that returns the value of a quadratic function at a particular x value. A quadratic is a polynomial of the form

$$ax^2 + bx + c$$

The function **quad()** is passed values for **a**, **b**, **c**, and **x** and returns the value of the polynomial.

5. A quadratic polynomial has a root at any value **x** for which the value of the polynomial is zero; that is, any x such that

$$ax^2 + bx + c = 0$$

There can only be at most two such values (a tuple), and the expression for finding these values of x is

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Write a function (**root(a,b,c)**)that returns the two roots of a quadratic equation having been passed a, b, and c. The result is a tuple or if there is no solution (i.e., square root of a negative number, or a=0), then it returns **None**.

6. Write a function (**inputfloat(s)**) that takes a single parameter, a string to be used as a prompt, and returns a number read from the console. The function must prompt the user for the number using the given string, read the input, and return the result as a floating point number. If an error occurs, return **None**.

7. The game of table tennis is called *ping-pong*. Write functions **ping()** and **pong()** that each take, as a parameter, a probability of hitting the ball. A probability is between 0.0 and 1.0. The function returns **True** if the ball is returns and **False** otherwise. There are two sides to the game, and each side serves (plays first) twice, then the other side serves twice. It will be assumed here that the server always succeeds. If ping is serving then **pong()** gets called first, then if pong succeeded then **ping()** gets called, and so on. The side that made the last successful hit wins a point. The game goes to 11 points, but must be won by a 2-point margin. Write a program that simulates *ping-pong* using two functions named **ping()** and **pong()**.

8. In *mutual recursion*, two functions call each other, usually repeatedly to some depth. **A** calls **B**, which calls **A** again, which calls **B** again, and so on. Recode the *ping-pong* exercise (Number 7 above) so that **ping()** calls **pong()** and **pong()** calls **ping()**. The functions return a string, that of the winner of the exchange.

9. Write a function **prime(n)** that returns **True** if the number **n** is prime, and **False** otherwise. How many prime numbers are there between 1 and 1000?

Notes and Other Resources

Tutorial on Python Functions: *http://www.tutorialspoint.com/python/python_functions.htm*

Also: *http://anh.cs.luc.edu/python/hands-on/3.1/handsonHtml/functions.html*

1. Thomas S. Ferguson, *Game Theory. https://www.math.ucla.edu/~tom/Game_Theory/comb.pdf*

2. D. G. Luenberger, (1973). *Introduction to linear and nonlinear programming* (Vol. 28). Reading, MA: Addison-Wesley.

3. Mitchell Wand (1980). *Induction, Recursion, and Programming*. North Holland, New York. *http://tocs.ulb.tu-darmstadt.de/82570701.pdf*

Chapter 5

Files: Input and Output

In this chapter

In the early days of computing, when computers used to fill an entire room, the file was invented. A *file* is a collection of bytes stored on a disk or similar device. Storage that was not memory was called secondary storage and was slow compared to how fast a computer could execute instructions (which is very slow compared to how fast a modern computer can execute instructions).

A typical PC has hundreds of thousands of files. The details of how files are implemented is interesting, but unimportant to the discussion of how to use them in Python. The focus is on how and why to use them.

One set of bytes in a file can look very much like another, and unless the format of the file (i.e., the way the bytes are ordered) and its basic contents (i.e., what kind of thing the bytes represent) are known ahead of time, the information stored there is unusable. Computer programs are written assuming that the files they will read have a particular nature; if a file does not have that nature, then the program will not function properly.

What kinds of files are there? Here is a short list:

Text files. These contain characters that a person can read and can be thought of as documents.

Executable files. These hold instructions that a computer can execute. Such a file is a program or an app.

Data files. It could also be a text file if it is stored as characters, but it could be a set of bytes that represent integers or real numbers.

Image files. There are many types of image files, and they contain pictures in digital format. Many digital cameras use a format called JPEG, but GIF or PNG are two of many others. Not only are images stored in such a file, but also data about how large the image is, when it was taken, and other details.

Sound files. The more common sound file is the MP3, but there are many others.

Video. MPEG and AVI are standard formats for video, and there are a many files of this sort available on the Internet.

Web pages. These are a special kind of text file. They can be examined and modified using basic text editors, but cannot be viewed properly (i.e., as a web page) except through a browser, which is really a special kind of display utility that can both draw images and connect to the Internet to download more information.

All of these files, and indeed all files, have certain things in common. Some of these things can be ignored when writing Python programs, but others cannot.

Files have names. The first way to access a file is usually by specifying its name. In folklore, knowledge of a true name allows one to affect another person or being; knowing something's true name gives the person power over that thing, and so it is with files. Knowing the name of a file is the way to access the information within.

Files have a size. It is usually expressed in bytes, which is to say, simple characters. One byte is one traditional alphabetic character, although there are now many standards for characters in German and Swedish and Chinese that break that rule. Knowing how large a file is helps when using it as input, and when writing a file, its size grows.

Basic operations on a file are *read* and *write*. To read from a file means to examine a byte (at least); usually bytes are read in large blocks for efficiency. This means moving a copy of the bytes from the disk into memory, because a program can only examine data that is in memory. Writing is the reverse process: a byte or bytes are copied from memory onto disk.

Files must be *open* before they can be used. To open a file, a program must know its name, and then invoke the *open* function or program. If the true name of the file gives you power over it, then *open* is the spell used to wield that power. Whether a file will be read or written is normally decided at the time the file is opened. The *open* function and many other file-related operations belong to the operating system of the computer, and not normally to the language. It's one reason why so much software is not portable.

Only one program at a time can write to a file. Many programs can read a file simultaneously, but only one can write to it, and not while anyone else is reading it. Many computers can have more than one user accessing a file at a time, and the Internet allows many users to access a Web page at one time, and a Web page is a file. However, chaos ensues if more than one user can change a file at the same moment.

Another thing to consider is that text (and therefore text files) is a principal means for communication between humans and computers. It is critical that any scheme for writing text to a file takes into account the human aspects of text: sentences, lines, paragraphs, special characters, and numbers. This chapter is concerned with the way in which Python can use files, with files as a concept in general, and with how humans think of data and files.

5.1 WHAT IS A FILE? A LITTLE THEORY

A file is a collection of bytes stored on a disk or similar device, but we need an understanding of the devices that contain files and their advantages and limitations. This information will begin to explain the traditional mechanisms that have evolved for using files from programming languages generally and Python in particular.

The file as a data structure was devised for storing information on tapes and disks. Together with some other devices that are used rarely (e.g., cram files), these are referred to as *secondary storage*, where primary storage is the computer's memory. Memory was (and still is) too expensive to store everything that is needed on a computer, so secondary storage has the advantages of being cheaper than memory and can contain a much larger amount of data. Modern disks can contain terabytes of data, where one terabyte (Tb) is 10^{12} bytes. It has been estimated that a human being's functional memory is about 1.25 Tb. A terabyte is a lot of storage.

Most secondary storage devices store data magnetically. Since tapes are rarely seen anymore, the example presented here is that of a disk. A disk is a circular platter made of glass or ceramic material and coated with a thin layer of magnetic material, often a compound of iron. That's why they look brown: iron oxide (or rust) is that color. The disk is mounted on a spindle that is connected to a motor, which spins it at a high rate of speed.

A device called a read/write head sits above the moving disk, but very near to it. This device is a small piece of magnetizable metal wrapped in a fine wire, not unlike the read/write heads in an old video tape recorder (VCR) or cassette machine. It is a property of magnets and coils that a moving magnet creates (induces) an electric current in a nearby coil, and a coil with a current flowing through it can create a magnetic field.

To write data to the moving disk, a current is sent to the read/write head, which creates a small magnetic mark on the disk below the head. Magnets have two orientations; they have a north pole and a south pole. Current flowing one way creates a magnet in the disk that has a north pole appearing before the south pole, or an N-S mark. Current flowing the other direction through the head creates a magnet on the disk that has the south pole appearing before the north pole, or an S-N mark. One orientation, say N-S, will represent a binary number 1, and the other (S-N) will represent a 0. In this way, binary numbers can be written to the surface of the moving disk.

Reading numbers involves the magnetic regions of the disk passing quickly past the read/write head and inducing small currents in the coil. These are amplified and classified by a simple electronic circuit that detects the current flow one way as N-S and another way as S-N, thus allowing binary numbers to be read from the disk.

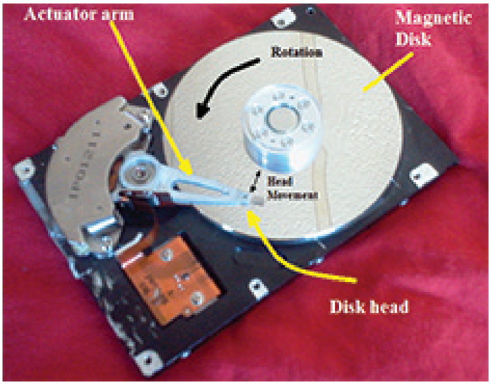


Figure 5.1
A disk drive with the cover removed show the key parts.

There are some very complicated physics involved in a disk drive. The read/write head must be very close to the surface of a rapidly rotating disk, as close as 3 nanometers. To accomplish this, the head is aerodynamically *flying* above the disk. If it ever touches the disk's surface, the result is catastrophic. At the speeds involved, a large section of the magnetic material on the disk's surface would be scraped away, and all data there would be lost. In addition, the read/write head would almost certainly be damaged. This event is called a *head crash*, and normally results in the entire disk drive being ruined. It's one reason that frequent backup copies of all data should be made.

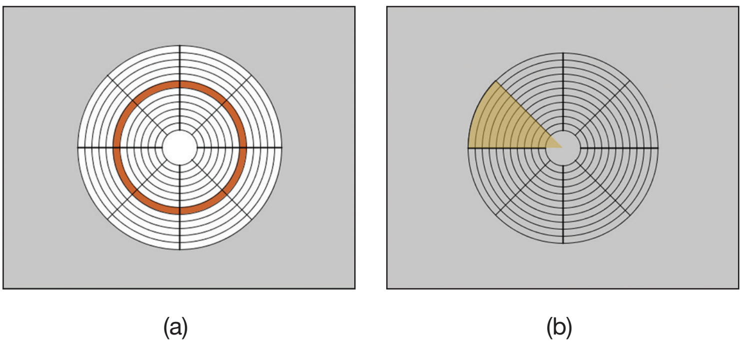


Figure 5.2
A track is the set of data from one circle on the disk. Inner tracks are smaller, but contain the same amount of data. (b) A sector is a wedge-shaped portion of the disk. The combination (track, sector) gives an address for a block of data.

The picture that is developing is that of a device that returns data as a stream of bits. To make the best use of the area of the disk, the read/write head can move from the outer edge of the disk to nearly the center. Imagine a set of concentric circles on the disk's surface: the moving read head can position itself over any of them and read the data that had been written there.

The disk is divided into a set of concentric circles called *tracks*, each of which corresponds to one position of the read/write head (Figure 5.2a). The head can move across the disk surface, but the positions are quantized: position 0-N_{tracks} can be reached through commands to a controller that change the head position. The outermost track is numbered 0, and the numbers increase as the head moves inward to the center. The disk is also divided into sectors, each of which is a wedge-shaped portion of the disk (Figure 5.2b). These are again numbered 0 to $N_{sectors}$, and create an address for a set of bits. Data can be read from sector 3 track 12 by positioning the read head over track 12 and waiting for sector 3 to rotate into position under the head. The data takes as long to read as the sector takes to pass under the read head.

This description answers two important questions. First, data can be accessed by using the <track, sector> address. The data in a single track and sector is a *block*, and all blocks are the same size in terms of bits for the sake of convenience, traditionally 512 bytes (4096 bytes for AF drives). Second, it explains why accessing data takes so long when reading from a disk. Disks rotate at 7200 RPM or 120 revolutions per second; this is one rotation every 8.3 milliseconds.

5.1.1 How Are Files Stored on a Disk?

A file can be thought of as a set of blocks. If blocks are 512 bytes in size and some data to be stored in a file consists of N bytes, then that file will need [*N*/512] blocks, the next larger integer than N/512; it's not possible to have two files share a single block.

It gets more complicated, though, because it will not always be possible to have all of the blocks that belong to a file lie next to each other. A file might consist of many blocks, all of which are some distance apart in terms of their track and sector. There is a need for a data structure to connect these blocks in the correct order to make a file. It's not very hard to do but is another step. This data structure is written to the disk also. The result is that reading a file means finding the location of this data structure on the disk, getting the track and sector values, and then reading the data from those and copying it into memory. The data structure containing the sectors is usually found through a *file name* that the user has provided. There is a list of file names and the track/sector address of their *index sectors* in a special file someplace on the drive, or in many places. File systems tend to be organized hierarchically, so that one main name is accessed to find the files within that part of the disk (*directory*), and within that directory are names of more files and directories. It is a significant part of the function of an operating system like *Linux* or *Windows* to provide a convenient way to access files.

5.1.2 File Access is Slow

How long does it take to access a block of data on the disk? It depends on where the disk head is and where the disk rotation has placed the target block at the time the request is made. There will be only a statistical answer, but for a random block, it could take an average of 10 mS to move the head to the correct track (*seek time*), and will take half of a rotation (4.15 mS). Add to this the time needed to read the block, which is 8.3*1/ $N_{sectors}$ mS, or about 0.008 mS for a disk with 1024 sectors. This can be ignored, and the time to access a random block can be estimated as 14.15 *milliseconds*.

As a comparison, fast computer memory can access data within 8 *nanoseconds*. If a person could write the word "Gigabyte" on a whiteboard in 8 nanoseconds, then what could they do in 14 milliseconds? They could copy the entire Bible onto the board over 16 times. Disks are vastly slower than memory, and to use the data, it must be copied into memory. This is a bottleneck in many computer systems.

5.2 KEYBOARD INPUT

Reading data from the keyboard is very different from reading data from a file. Files exist before being read, and normally have a fixed size that is known in advance. It is common to know the format of a file, so that the fact that the next datum is an integer and the one following that is a float is often known. When a user is entering data at a keyboard, there is no such information available. In fact, the user may be making up the data as they go along. Before getting too far into file input, it is important to understand the kind of errors that can happen interactively.

These are using type errors, where the user enters data that is the wrong type for the programmer to use: a string instead of an integer, for example. This kind of error can arise in file input if the format is not known in advance.

5.2.1 Problem: Read a number from the keyboard and divide it by 2

This problem addresses how to treat integers like integers and floats like floats. When the string s is read in, it is just a string, and it is supposed to contain an integer. However, users will be users, and some may type in a float by mistake. The program should not crash just because of a simple input mistake. How is this situation handled?

The problem is that when the string is converted into an integer, if there is a decimal point or other non-digit character that does not belong then an error will occur. It seems that an answer would be to put the conversion into a **try** statement block and if the string has a decimal point, then convert the string to a float within the **except** part. The code looks like this:

```
s = input("Input an integer: ")
try:
    k = int(s)
    ks = k//2
except:
    z = float(s)
    k = int(z/2)
print (k)
```

If the user types "12" in response to the prompt "Input an integer:," then the program prints "6." If the user types "12.5," then the program catches a **ValueError**, because 12.5 is not a legal integer. The except part is executed, converting the number to floating point, dividing by 2, then finally converting to an integer.

One problem is that the **except** part is not part of the **try**, so errors that happen there will not be caught. Imagine that the user types "one" in response to the prompt. The call to **int(s)** results in a **ValueError**, and the **except** part is executed. The statement

```
z = float(s)
```

results in another **ValueError**. This one will not be caught and the program will stop executing, giving a message like:

```
ValueError: could not convert string to float: 'one'
s = input("Input an integer: ")
try:
    k = int(s)
    k = k//2
except ValueError:
    try:
      z = float(s)
      k = int(z/2)
    except ValueError:
      k = 0
print (s, k)
```

5.3 USING FILES IN PYTHON: LESS THEORY, MORE PRACTICE

The general paradigm for reading and writing files is the same in Python as it is in most other languages. The steps for reading or writing a file are these:

1. **Open the file**. This involves calling a function, usually named **open**, and passing the name of the file to be used. Sometimes the *mode* for opening is passed; that is, a file can be opened for input, output, update (both input and output), and in binary modes. The function locates the file using the name and returns a variable that keeps track of the current state of input from the file. A special case exists if there is no file having the given name.
2. **Read data from the file**. Using the variable returned by **open**, a function is called to read the data. The function might read a character, number, line, or the whole file. The function is often called **read**, and can be called multiple times. The next call to **read** will read from where the last call ended. A special case exists when all of the data has been read from the file (called the *end of file* condition)

   OR

   Write data to the file. Using the variable returned by **open**, a function is called to write data to the file. The function might write a character, number, line, or many lines. The function is often called **write**, and can be called multiple times. The next call to **write** will continue writing data from where the last call ended. Writing data most frequently appends data to the end of the file.

3. **Close the file**. Closing a file is also accomplished using a call to a function (usually named **close**). This function frees storage associated with the input process and in some cases unlocks the file so it can be used by other programs. A variable returned by **open** is passed to **close**, and afterwards that variable cannot be used for input anymore. The file is no longer open.

5.3.1 Open a File

Python provides a function named **open** that opens a file and returns a value that can be used to read from or write to the file. That value refers to a complex collection of values that refers to the file status and is called a *handle* or a *file descriptor*. It can be thought of as having the type *file*, and must be assigned to a variable or the file cannot be accessed. The **open** function is given the name of the file to be opened, and a flag that indicates whether the file is to be read from or written to. Both of these are strings. A simple example of a call to open is as follows:

```
infile = open ("datafile.txt", "r")
```

This opens a file named “datafile.txt” that resides in the same directory as does the Python program, and opens it for input: the “r” flag means *read*. It returns the handle to the variable **infile**, which can now be used to read data from the file.

There are some details that are crucial. The name of the file on most computer systems can be a path name, which is to say, the name including all directory names that are used to find it on your computer. For example, on some computers, the name “datafile.txt” might have the complete path name *C:/parker/introProgramming/chapter05/datafile.txt*. If path names are used, the file can be opened from any directory on the computer. This is handy for large data sets that are used by multiple programs, such as names of customers or suppliers.

The read flag “r” that is the second parameter is what was called the mode in the previous discussion. The “r” flag means that the file will be open for reading only, and starts reading at the beginning of the file. The default is to read characters from the file, which is presumed to be a text file. Opening with the mode “rb” opens the file in binary format and allows reading non-text files, such as MP3 and video files.

Passing the mode "w" means that the file is to be written to. If the file exists, then it will be overwritten; if not, the file will be created. Using "wb" means that a binary file is to be written.

Append mode is indicated by the mode parameter "a," and it means that the file will be opened for writing and if the file exists then writing will begin at the end of the existing file. In other words, the file will not start over as being empty, but will be added to, at the end of the file. The mode "ab" appends data to a binary file.

If the file does not exist and it is being opened for input, there is a problem. It's an error, of course; a non-existent file cannot be read from. There are ways to tell whether a file exists, and the error caused by a non-existent file can be caught and handled from within Python. This involves an **exception**. It is always a bad idea to assume that everything works properly, and when dealing with files it is especially important to check for all likely problems.

File Not Found Exceptions

The proper way to open a file is within a **try-except** pair of statements. This ensures that nonexistent files or permission errors are caught rather than causing the program to terminate. The basic scheme is simple:

```
try:
  infile = open ("datafile.txt", "r")
except FileNotFoundError:
  print ("There is no file named 'datafile.txt'.
          Please try again")
  return            # end program or abort this section
                    # of code
```

The exception **FileNotFoundError** occurs if the file name cannot be found. What to do in that case depends on the program: if the file name was typed in by the user, then perhaps they should get another chance. In any case, the file is not open and data cannot be read.

There are multiple versions of Python on computers around the world, and some versions have different names for things. The examples here all use Python 3.4. In other versions, the **FileNotFoundError** exception has another name; it may be **IOError** or even **OSError**. The documentation for the version being used should be consulted if a compilation error occurs when using exceptions and some built-in functions. For the 3.4 compiler version, all three seem to work with a missing file.

All attempts to open a file should take place while catching the **FileNotFoundError** exception.

5.3.2 Reading from Files

After a file is opened with a read mode, the file descriptor returned can be used to read data from the file. Using the variable **infile** returned from the call to **open()** above, a call to the method **read()** can get a character from the file:

```
s = infile.read(1)
```

Reading one character at a time is always good enough, but is inefficient. If a block on disk is 512 characters (bytes), then that should be a good number of bytes to read at one time or a multiple of that. Reading more data than you need and saving it is called *buffering*, and buffers are used in many instances: live video and audio streaming, audio players, and even in programming language compilers. The idea is to read a larger block of data than is needed at the moment and to hand it out as needed. Reading a buffer could be done as follows:

```
s = infile.read(512)
```

and then dealing characters from the strings one at a time as needed. A buffer is a collection of memory locations that is temporary storage for data that was recently on secondary storage.

Text files, those that contain printable characters that humans can read, are normally arranged as lines separated by a carriage return or a linefeed character, called a *newline*. An entire line can be read using the **readline()** function:

```
s = infile.readline()
```

A line is not usually a sentence, so many lines might be needed to read one sentence, or perhaps only half of a line. Computer text files are structured so that humans can read them, but the structure of human language and convention is not understood by the computer nor it is built into the file structure. However, it is normal for people to make data files that contain data for a particular item or event on one line, followed by data for the next item. If this is true, then one call to **readline()** will return all of the information for a particular thing.

End of File

When there are no more characters in the file, **read()** will return the empty string: “”. This is called the *end of file condition*, and it is important that it be detected. There are many ways to open and read files, but for reading characters in this way, the end of file is checked as follows:

```
infile = open("data.txt", "r")
while True:
  c = infile.read(1)
  if c == '':
    print ("End of file")
    exit()
  else:
    c = infile.read(1)
```

When reading a file in a **for** statement, the end of file is handled automatically. In this case, the loop runs from the first line to the final line and then stops.

```
for c in f:
    print ("'", c, "'")
```

An exception cannot be used in an obvious way for handling the end of file on file input. However, when reading from the console using the input() function, the exception **EOFError** can be caught:

```
while True:
  try:
      c = input()
      print (c)
  except EOFError:
      print ("Endfile")
      break
```

There are many errors that could occur for any set of statements. It is possible to determine what specific exception has occurred in the following manner:

```
while True:
  try:
      c = input()
      print (c)
  except Exception as x:
      print (x)
      break
```

This code prints "EOF when reading a line" when the end of file is encountered.

Common File Input Operations

There are a few common ways to use files that should be mentioned as *patterns*. Although one should never use a pattern if it is not understood, it's sometimes handy to have a few simple snippets of code that are known to perform basic tasks correctly. For example, on common operation to use with files is to **read each line from a file**, followed by some processing step. This looks like

```
f = open ("data.txt", "r")
for c in f:
    print ("'", c, "'")
f.close()
```

The expression **c in f** results in consecutive lines being read from the files into a string variable **c**, and this stops when no more data can be read from the file.

Another way to do the same thing would be to use the **readline**() function:

```
f = open ("data.txt", "r")
c = f.readline()
while c != '':
    print ("'", c, "'")
    c = f.readline()
f.close()
```

In this case, the end of file has to be determined explicitly by checking the string value that was read to see if it is null.

Another common file operation is to **copy a file to another**, character by character. A file is opened for input and another for output. The basic "read a file" pattern is used, with the addition of a file output after each character is read:

```
f = open ("data.txt", "r")
g = open ("copy.txt", "w")
c = f.read(1)
while c != '':
    g.write(c)
    c = f.readline(1)
f.close()
g.close()
```

A **filter** is a program that reads data from a file and converts it to some other form, then writes it out. This is often done from standard input and output, but can be done in the middle of a file copy. For example, to convert a text file to all lower case, the pattern above is used with a small modification:

```
f = open ("data.txt", "r")
g = open ("copy.txt", "w")
c = f.read(1)
while c != '':
    g.write(c.lower())
    c = f.readline(1)
f.close()
g.close()
```

This filter can be done using less code if the entire file can be read in at once. The **read**() function can read all data into a string.

```
f = open ("data.txt", "r")
g = open ("copy.txt", "w")
c = f.read()
g.write(c.lower())
f.close()
g.close()
```

Two files can be merged into a single file in many ways: one file after another, a line from one file followed by a line from another, or character by character. A simple merging of two files where one is copied first followed by the other is as follows:

```
f = open ("data1.txt", "r")
outfile = open ("copy.txt", "w")
c = f.read()
outfile.write(c)
f.close()
g = open ("data2.txt", "r")
c = g.read()
outfile.write(c)
g.close()
outfile.close()
```

A more complex problem occurs when both files are sorted and are to **remain sorted after the merge**. If each line is in alphabetical order in each file, then merging them means reading a line from each and writing the one that is smallest. When one file is complete, the remainder of the second file is written and all files are closed.

```
f = open ("data1.txt", "r")
g = open ("data2.txt", "r")
outfile = open ("copy.txt", "w")
cf = f.readline()
cg = g.readline()
while cf!="" and cg!="":
    if cf<cg:
        outfile.write(cf)
        cf = f.readline()
    else:
        outfile.write(cg)
        cg = g.readline()
if cf == "":
    outfile.write(cg)
    cg = g.read()
    outfile.write(cg)
else:
    outfile.write(cf)
    cf = f.read()
    outfile.write (cf)
f.close()
g.close()
outfile.close()
```

Copying the input from the console to a file means reading each line using **input**() and writing it to the file. This code assumes that an empty input line implies that the copying is complete.

```
outfile = open ("copy.txt", "w")
line = input ("! ")
while len(line)>1 or line[0]!="!":
    outfile.write(line)
    outfile.write ("\n")
    line = input("! ")
outfile.close()
```

The end of the line is indicated by a character, which is represented by the string “\n”. Reading characters from a file will read the end of line character also, and detecting it can be very important.

```
f = open ("data.txt", "r")
```

```
c = f.read(1)
while c != '':
    print ("'", c, "'")
    c = f.read(1)
    if c == '\n':
        print ("Newline")
```

CSV Files

A very common format for storing data is called Comma Separated Variable (CSV) format, named for the fact that each pair of data items have a comma between them. CSV files can be used directly by spreadsheets such as Excel and by a large collection of data analysis tools, so it is important to be able to read them correctly.

A simple CSV file named ***planets.txt*** is provided for experimenting with reading CSV files. It contains some basic data for the planets in Earth's solar system, and while there is no actual standard for how CSV files must look, this one is typical of what is usually seen. The first line in the file contains headings for each of the variables or columns, separated by commas. This is followed by nine lines of data, one for each planet. It's a small data file, as these things are counted, but illustrative for the purpose.

Table 5.1
CSV data for the planets

Name,	Mass,	Diam,	Density,	Grav,	Escape,	Rotation,	Day,	Dis- tance,	Period,	Moons,	Temp
Mercury,	0.364,	3032,	339,	12.1,	2.7,	1407.6,	4222.6,	36.0,	88.0,	0,	333
Venus,	5.37,	7521,	327,	29.1,	6.4,	-5832.5,	2802.0,	67.2,	224.7,	0,	867
Earth,	6.58,	7926,	344,	32.1,	7.0,	23.9,	24.0,	93.0,	365.2,	1,	59
Mars,	0.708,	4221,	246,	12.1,	3.1,	24.6,	24.7,	141.6,	687.0,	2,	-85
Jupiter,	2093,	88846	83,	75.9,	37.0,	9.9,	9.9,	483.8,	4331.0,	67,	-166
Saturn,	627,	31783	43,	29.4,	22.1,	10.7,	10.7,	890.8,	10747,	62,	-220
Uranus,	95.7,	31763	79,	28.5,	13.2,	-17.2,	17.2,	1784.8,	30589,	27,	-320
Neptune,	113.0,	30775	102,	36.0,	14.6,	16.1,	16.1,	2793.1,	59800,	14,	-330
Pluto,	0.0161,	1464	131,	2.3,	0.8,	-153.3,	153.3,	3670.0,	90560,	5,	-375

Problem: Print the names of planets having fewer than ten moons.

This is not a very profound problem, and uses the raw data as it appears on the file. The file must be opened and then each line of data is read, and the value of the 11th data element (i.e., index 10) retrieved and compared against 10. If larger, the name of the planet (index 0) is printed. The plan is as follows:

Open the file

Read (skip over) the header line

For each planet

  Read a line as string **s**

  Break **s** into components based on commas giving list **P**

  If **P[10] < 10,** print the planet name, which is **P[0]**

It is all something that has been done before except for breaking the string into parts based on the comma. Fortunately, the designers of Python anticipated this kind of problem and have provided a very useful function: **split()**. This function breaks up a string into parts using a specified delimiter character or string and returns a list in which each component if one section of the fractured string. For example,

```
s = "This is a string"
z = s.split(" ")
```

yields the list z = [“This”, “is”, “a”, “string”]. It splits the string **s** into substrings at each space character. A call like **s.split(“,”)** should give substrings that are separated by a comma. Given the above outline and the **split()** function, the code is as follows.

```
try:
# Open the file
    infile = open ("planets.txt", "r")
# Read (skip over) the header line
    s =infile.readline()
# For each planet
    for i in range (0, 8):
# Read a line as string s
        s = infile.readline()
# Break s into components based on commas giving list P
        P = s.split (",")
# If P[10] < 10 print the planet name, which is P[0]
        if int(P[10])<10:
            print (P[0], " has fewer than 10 moons.")
except FileNotFoundError:
        print ("There is no file named 'planets.txt'.
                Please try again")
```

Almost the entire program resides within a try statement, so that if the file does not exist, then a message is printed and the program ends normally. Note that P[10] has to be converted into an integer, because all components of the list P are strings. Strings are what has been read from the file.

CSV files are common enough so that Python provides a module for manipulating them. The module contains quite a large collection of material, and for the purposes of the *planets.py* program, only the basics are needed. To avoid the details of a general package, a simpler version is included with this book: *simpleCSV* has the essentials needed to read most CSV files while being written in such a way that a beginning programmer should be able to read and understand it.

To use it, the **simpleCSV** module is first imported. This makes two important functions available: **nextRecord()** and **getData()**. The **nextRecord()** function reads one entire line of CSV data. It allows skipping lines without examining them in detail (like headers). The function **getData()** will parse one line of data, the last one read, into a tuple, each element of which is one of the comma-separated fields.

The *simpleCSV* library needs to be in the same directory as the program that uses it or be in the standard Python directory for installed modules. The source code resides on the accompanying disk and is called *simpleCSV.py*. The program can be re-written to use the *simpleCSV* module as follows:

```
import simpleCSV
try:  # Read (skip over) the header line
    infile = open ("planets.txt", "r") # Open the file
    simpleCSV.nextRecord(infile)       # Read the header
    for i in range (0, 8):             # For each planet
        simpleCSV.nextRecord(infile)   # Read a line and
                                       # collect substrings
                                       # in a list
        p = simpleCSV.getData(infile)
        if int(P[10])<10:       # If number of moons
                                # less than 10
            print (P[0], " has fewer than 10 moons.")
                                     # print the planet name
except FileNotFoundError:
        print ("There is no file named 'planets.txt'.
                Please try again")
```

Problem: Play *Jeopardy* using a CSV data set.

The television game show *Jeopardy* has been on the air for 35 years in one of its two incarnations, and is perhaps the best known such program on television. Players select a topic and a point value and are asked a trivia question that they must answer in the form of a question. There are sets of questions that have been used in Jeopardy over the years, some in CSV form, and so it should be possible to stage a simulated game using Python as the moderator.

A simple version of the game could work like this: read the questions and answers, and select the questions at random. Questions that have single-word unambiguous answers would be best. The player types in an answer, and wins if they answer ten correctly before getting three wrong.

A single line of data from the file might look like this:

```
5957,2010-07-06,Jeopardy!,"LET'S  BOUNCE","$600","In  this
kid's game, you bounce a small rubber ball while picking up
6-pronged metal objects","jacks"
```

There are 7 different data fields here separated by commas. They are: Show Number, Air Date, Round, Category, Value, Question, and Answer; all are strings, but some questions may contain commas. The CSV module can manage that.

There are many ways that a random question can be chosen. One would be to read all of the data into a list, but that would require a lot of memory. Another way would be to randomly read a question from the file, but that would be difficult to do because each line has a different length. What could be done relatively easily would be to pick a random number of questions to skip over before reading one to use. We therefore select a random number K between N and M, read K questions, and then read the next one and ask the user that question. When the end of the file is reached, it can be read again from the beginning. If the file is large enough, it would be unlikely to ask the same question twice in a short time period.

Here is an outline of how this might work:

```
Open infile as the file of questions to be used
While game continues:
    Select a random number K between N and M
    For I = N to M:
       Read a line from the file
        If no more lines:
```

```
                Close infile and reopen
    Read a question and print it, ask the user for an answer
    Read the user's answer from the keyboard
    If the user's answer is correct:
           Count right answers
    Else:
           Count wrong answers
```

If the CSV module is used the parsing the input file is dealt with. What is new about his? When all of the data in the file has been used the program may not be complete. What is done then is new: close the file, reopen it, and start again from the beginning. This is an unusual action for a Python program but illustrates the flexibility of the file system. There is a nested try-except pair, the outer one that checks the existence of the file of questions and the inner one that checks for the end of the file. When the file is re-opened, a new **reader** has to be created, because the old one is connected to a closed file. The file on the disk is the same, but when it is opened again, a new handle is built; the old CSV **reader** is linked to the old handle.

The program counts the number of right answers (**CORRECT**) and the number of wrong ones (**INCORRECT**). When there are 10 correct answers or 3 incorrect ones, the game is over; a variable **again** is set to **False** and the main **while** loop exits. A **break** could have been used, but having the condition become **False** is the polite way to exit from a **while** loop.

The entire program looks like this:

```
# Jeopardy!
import simpleCSV, random

try:
    infile = open ("q.txt", "r")   # Open the file
    simpleCSV.nextRecord(infile)   # Read (skip over) the
                                   # header line

    CORRECT = 0
    INCORRECT = 0
    again = True
    while again:
        k = random.randint (5, 10) # How many questions
                                   # to skip?
```

```
        for I in range (0, k):
            if not simpleCSV.nextRecord(infile):
                                                # Skip this question
                infile.close()
                print ""Reopenin"")
                infile = open ""JEOPARDY_small.tx"","""")
                simpleCSV.nextRecord(infile)
        s = simpleCSV.getData(infile)   # Read the question
                                        # to be asked.
        print (s[5])                    # Print the question
        a = input ()                    # Read the answer
        if a.lower() == s[6].lower():   # Does player answer
                                        # agree?
            CORRECT = CORRECT + 1       # Yes. count to 10.
            if CORRECT >= 10:
                print ""You win"")
                again = False
        else:
            INCORRECT = INCORRECT + 1   # No. Count to 3
            print ""Sorry. The answer is"", s[6])
            if INCORRECT > 12:
                print ""You lose"")
                again = False
except FileNotFoundError:
        print ""There is no question file.  We can't play"")
```

The With Statement

A difficulty with the code presented so far is that it does not clean up after itself. A file should be closed after input from it or output to it is finished; none of the programs written so far do that, at least not after the file operations are complete. There has been no significant discussion of the **close()** operation, but what it does has been described. Normally, when a program terminates, its resources are returned to the system, including the closing of any open files. Intentionally closing a file is important for three reasons: first, if the program aborts for some reason, open files *should* be closed by the system but may not be, and file problems can be the result. Second, as in the *Jeopardy* program, closing a file can be used as a step in re-using it. Opening it again starts reading it at the beginning. Third, closing a file frees its resources. Programs that use many files and/or many resources will profit from freeing them when they are no longer needed.

The Python *with* statement, in its simplest form, takes care of many of the details surrounding file access. An example of its use is as follows:

```
try:
   with open ("planets.txt") as infile:  # Open the file
       simpleCSV.nextRecord(infile)       # Read the header
       for i in range (0, 9):             # For each planet
           simpleCSV.nextRecord(infile)   # Read a line,
                                          # make a list
           P = simpleCSV.getData(infile)
           if int(P[10])<10:            # If number of moons
                                        # less than 10
               print (P[0], " has fewer than 10 moons.")
                                              # print the name
except FileNotFoundError:
       print ("There is no file named 'planets.txt'.
               Please try again")
```

Once the file is open, the *with* statement guarantees that certain errors will be dealt with and the file will be closed. The problem is that the file has to be open first, so the **FileNotFound** error should still be caught as an exception.

5.4 WRITING TO FILES

The first step in writing to a file is opening it, but this time for output:

```
outfile = open ("out.txt", "w")
```

The "w" as the second parameter to **open()** means to open the file for writing. When writing to a file, it is important to note that opening it will create a new file by default. If a file with the given name already exists, it will be re-written, and the previous contents will be deleted.

The basic file output function is **write()**; it takes a parameter, a string to be written to the file. It only writes strings, so numbers and other types have to be converted into strings before being written. Also, there is no concept of a line. This function simply moves characters to a file, one at a time, in the order given. In order to write a line, an end of line character has to be written. This is usually specified in a string as \n, spoken as "backslash n." The "n" stands for newline.

Example: Write a table of squares to a file.

This example illustrates the typical code involved in writing to a file. The file must be opened, then a loop from 0 to 25 is constructed. Each number in that range is written to the file, as is that number multiplied by itself. Each output string represents a line, and so must have a newline character added to the end.

```
outfile = open ("out.txt", "w")
outfile.write ("    X             X squared \n")
for i in range (0, 25):
    sout = "    "+str(i)+"       "+str(i*i)+"\n"
    outfile.write (sout)
outfile.close()
```

Note that the integers are explicitly converted into strings and concatenated into a line to be written. The elements of the line could be written in separate calls:

```
outfile = open ("out.txt", "w")
outfile.write ("    X             X squared \n")
for i in range (0, 25):
    outfile.write ("    ")
    outfile.write (str(i))
    outfile.write ("              ")
    outfile.write (str(i*i))
    outfile.write ("\n")
outfile.close()
```

The output file is closed after all data has been written.

5.4.1 Appending Data to a File

Opening the file in "w" mode starts writing at the beginning of the file, and will result in existing data being lost. This is not always desirable. For example, what if a log file is being created? The log should contain a record of everything that has happened, not just the most recent action.

Opening the file in *append* mode, signified by the parameter "a," opens the file for output and starts writing at the end of the file if it already exists. This means that data can be added to the end of an existing file.

Example: Append another 20 squares to the table of squares file.

The previous example created a file named "out.txt" and wrote 26 lines to it. It was a table of squares, and the final one was 24. This example will therefore begin at 25 and add 20 more values to the table.

The main difference is the opening of the output file in append mode, and starting the loop at 25 instead of at 0:

```
outfile = open ("out.txt", "a")
for i in range (25, 45):
      sout = "     "+str(i)+"                    "+str(i*i)+"\n"
      outfile.write (sout)
outfile.close()
```

The file "out.txt" will contain the squares of the integers between 0 and 44, inclusive, after this program runs.

5.5 SUMMARY

Files are computer structures within which data are stored, and almost always reside on disk devices, tape devices, or other secondary storage. Files have some common properties: files have names; files have a size; basic operations on a file are *read* and *write*; files must be *open* before they can be used; and only one program at a time can write to a file. Access to data on a file is much slower than access to data in memory, but file data has to be moved into memory before it can be manipulated.

Exceptions are events that occur while a program is executing, such as dividing by zero. Rather than check for all possible exceptions every time a statement is executed, Python provides a **try-except** statement that allows the programmer to provide code to run when an error occurs. Specific named exceptions exist in Python that can be specifically caught, like *ValueError*, or all exceptions can be caught by not specifying a particular one.

Files are opened using a call to open passing a file name and a mode. If the mode is "r," then the file will be read from; if it is "w," it will be written to (for example, **x = open("input.txt", "r")**). Reading from a file x is accomplished by a **read** call**: x.read(n)** will return a string of **n** characters; **x.readline()** will return one line from the file **x**. When there are no more characters in the file, **read()** will return the empty string: “”. This is called the *end of file condition*.

A CSV (*comma separated values*) file is a specific format that is common for some kinds of data, including spreadsheets. The *simpleCSV* package provided on the accompanying disk can be helpful in reading these files.

Output to a file **x** is done with a call to write: **x.write(s)** writes the string **s** to the file represented by x. The string “\n” represents the end of a line.

Note: This chapter will be extended in Chapter 8 to expand the kind of file operations and data that can be read from and written to a file.

Exercises

1. Write a program that reads a file name from the user (console) and prints out how many characters belong to that file.
2. Write a program that opens a file containing a list of file names. For each one print the file name followed by YES if that file exists in the current directory and NO if it does not.
3. Create a file copy facility. The program should read the name of a file from the user’s console and create another file with the same contents. If the original file is named “xx.txt,” then the new file will be named “xx-copy.txt.” The original file will always have a name ending in .txt, and so will the copy.
4. The CSV file “avatardata.csv” contains saved information concerning the preferred avatars for players of a video game. The fields are the player code (integer), avatar type (string, no quotes), number of times this avatar was played at this level (integer), a game level reached (integer, out of 12), and the highest score achieved on this level(integer); there is no header. Read this file and determine and print which player/avatar has the highest score on each level.
5. Using a Python program, create a CSV file from “avatardata.csv” that contains only information for level 10.
6. In an HTML file (i.e., a Web page), an image to be displayed is usually identified in a source tag of the form: **src=“name.jpg”**. The quotes are a part of the tag, and the text between them is an image file name. Write a program

that reads an HTML file and prints the names of all of the images files that it references.

7. A user will specify the name of an image file, such as a file having a name that ends in .jpg, .gif, or .png, from the console. Your program will read this name and create "disp.html," an html file that, when opened by a browser, will display this image. (This exercise requires a knowledge of basic HTML.)
8. Two files, named *sorted1.txt* and *sorted2.txt*, contain numeric data that appear in the file in sorted ascending order (when looked at as a string). Merge these two files to create a single file having the data of both, also in sorted order.

Notes and Other Resources

Python CSV Library: *https://docs.python.org/3/library/csv.html*

1. Remzi Arpaci-Dusseau and Andrea Arpaci-Dusseau (2015). *Operating Systems: Three Easy Pieces*. Amazon Digital Services, Inc.
2. Marco Cesati and Marco Cesati (2005) *Understanding the Linux Kernel*, O'Reilly Media.
3. Dominic Giampaolo (1999). *Practical Filesystem Design*, Morgan Kaufmann Publishers, Inc. *http://www.nobius.org/~dbg/practical-file-system-design.pdf* *www.nobius.org/~dbg/practical-file-system-design.pdf*
4. Robert Stetson (2013). *How Disk Drives Work*. CreateSpace Independent Publishing Platform.
5. Jeopardy questions: *https://docs.google.com/uc?id=0BwT5wj_P7BKXUl9tOUJWYzVvUjA&export=download*

Chapter 6

Classes

In this chapter

Classes, as a programming language feature, have been around since the 1960s. Design concepts in object-oriented programming and related subjects have been around nearly as long: since the 1970s. There are still arguments about how to teach about objects, and whether to teach them early in a programming course or later. Rather than try to solve this impossible problem, why not try multiple ways? Then people can choose which way they like best.

6.1 A CASUAL INTRODUCTION TO CLASSES

How many jokes begin with a phrase like "A man walks into a bar?" So many jokes begin with this line that when someone hears that phrase, they will assume whatever comes next is a joke. But what is a *man*, what is a *bar*, and what does *walking* entail? *Walking* seems to be something that a man can do, an action he can perform. A *bar* is a place where a *man* can *walk*. Can a *man* do anything else but *walk*? Is a *bar* the only place a man can *walk* to?

It seems silly to examine a sentence in that way, but in the context of a computer program, it is more meaningful. Imagine that this discussion involves a computer game or simulation. A *man* now represents some kind of thing or object that is manipulated by the program. A *man* has properties and things it can do, which is to say operations it can perform. What properties does a *man* object have? See Table 6.1 for a small subset of the possibilities.

Table 6.1
Properties of the "man" object

Property	Type
Name	String
Sex	Boolean
Phone number	Integer
Height	Float
Weight	Float
Job	String?
Home (location, address)	String?
Interests	Array of String
Income	Float
Possessions (other objects)	Array of object
Spouse	*person*
Children	Array of *person*

A *man* would appear to be a complex data type having a number of properties. Note especially that a man can have a property or characteristic called **spouse**. A **spouse** is something called a *person*; so is a *man*, really. This is abstract, but consider that a *man* is a *person*, and perhaps some of the characteristics of a *man* are really those of (i.e., inherited from) a *person*. In fact, it would appear that most of them are. The only thing that distinguishes a *man* from other persons would (from the list above) be *sex*, which would be (perhaps) **false** for a man and **true** for a *woman*, another kind of *person*.

Imagine that there is a whole class of things called *person* that have most of these properties. A *man* could be derived from this, since *man* has many of these properties in common. A *woman* could be another class, perhaps having a few different properties. A *man* could have, for example, a "date of last prostate exam" as a property, but a *woman* could not. A *woman* could have a "date of last pap smear," but a *man* could not. At some point, person has many common characteristics, but *man* has some that *woman* does not and vice versa.

Let us consider the original proposition: what is a *bar*? It is clearly a thing (object) that can hold (contain) a *man*. Perhaps it can contain many *men*. Can it contain *women*? Why not? If a *person* has to be either a *man* or a *woman*, then a bar can contain some number of *person*s. A *bar* is a class of objects that can hold or contain some number of *person*s. It would be a container class or a holder of some kind.

The phrase "A man walks into a bar" might be expressed as follows:

```
aMan.walksInto (aBar)
```

where **aMan** is a particular man (a specific instance of a man class) and aBar is a specific instance of a class of objects known as bar. This man has a Name, which is to say that one of the properties that a man has is a Name, and this is really just a variable. Since each individual *man* has a **Name** there has to be a way of getting at (accessing) each one. It is done through each instance:

```
print (aMan.Name)        # Accessing /printing the name.
aMan.Name = "Ted Smith" # Assigning to the name.
```

Using this syntax, the dot (.) is placed after the name of the instance. The syntax **aMan.Name** means "look at the variable **aMan**, which is an instance of *man*, for a property called **Name**."

What is the meaning of **walksInto** in the above expression **aMan.walksInto(aBar)**? Considering the syntax just described, it would appear to be a function that was a part of the definition of *man*. It takes one parameter, which is something having the type *bar*.

This way of looking at the "man walks into a bar" scenario seems sensible in that it organizes information and provides a clear and formal way to access it and manipulate it. This discussion has been a metaphor for the concept of a *class* and the ideas behind *object orientation*, two key elements of modern programming structures. Python permits the programmer to define classes like the *man* or *bar* objects previously described, and to use them to encapsulate variables and functions and create convenient modular constructions.

6.2 CLASSES AND TYPES

A *class*, in the general sense, is a template for something that involves data and operations (functions). An *object* is an instance of a class, a specific instantiation of the template. Defining a class in Python involves specifying a class name and a collection of variables and functions that belong to that class. The man class that has been referred to so far has only a few characteristics that we know about for certain. It does have a function called **walksInto**, as one example. A first draft of the man class could be as follows:

```
class man:
    def walksInto (aBar):
        # code goes here
```

A function that belongs to a class is generally referred to as a *method*. This terminology likely refers back to a language devised in the 1970s named *Smalltalk*. According to the standard for that language, *"A method consists of a sequence of expressions. Program execution proceeds by sequentially evaluating the expressions in one or more methods*."[5] In the above example, walksInto is a method; essentially, a method is any function that is part of a class.

Classes can have their own data too, which would be variables that belong to the class in that they exist inside it. Such variables can be used inside the class but should not be accessed from outside.

Looking closely at the simple class **man** above, notice that it is actually still an abstract thing. In the narrative about a man walking into a bar it was a specific *man*, as indicated by a variable **aMan**. A class is really a description of something, in that examples or instances should be created in order to make use of that description. This is correct. In fact, many individual instances of any class can be created (instantiated) and assigned to variables. To create a new instance of the class **man**, the following syntax could be used:

```
aMan = man()
```

When this is done, all of the variables used in the definition of man are allocated. In fact, whenever a new man class is created, a special method that is local to man is called to initialize variables. This method is the *constructor*, and can take parameters that help in the initialization. Creating a man might involve giving him a name, so the instantiation may be

```
aMan = man("Jim Parker")
```

In this case, the constructor accepts a parameter, a string, and probably assigns it to a variable local to the class (**Name**, most likely). The constructor is always named __init__:

```
def __init__ (self, parameter1, parameter2, …):
```

The initial parameter named **self** is a reference to the class being defined. Any variable that is a part of this class is referred to by prefixing the variable name with "self." To make a constructor for **man** that accepted a name, it would look like this:

```
def __init__ (self, name):
    self.Name = name
```

When a man is created, the statement would be as follows:

```
aMan = man ("Jim Parker")
```

6.3 CLASSES AS ENCAPSULATED MODULES

We have been exposed to Python *modules* or *packages* already: **math** and **random** are two examples. These are really a collection of variables and functions with a common theme or purpose that we can access when we need them. We don't have to create a random number function whenever we need one, we can just use the one within **random**. A class than be thought of as a module.

Within the module there are functions which, because they are part of a class, are called *methods*. Variables can be defined within a class and have a scope all their own. A variable named **x** can be declared within a class and also within other classes and the main program without any confusion.

A class can be *instantiated*, which means an instance or version of it is created. When we say **from random import *** at the beginning of a program, we are effectively creating an instance of *random*. That's how we get access to most of the variables and methods within it. We can instantiate random as

```
import random
s = random
```

As an instance of random, the methods can be accessed through **s** using the dot notation. For example,

```
print (s.random())
```

with print a random number. There can be multiple instances of a class, and each is created by referencing the class name.

```
s = random
t = random
print (s.random(), t.random())
```

This is not always useful, as in this case, but can be when the class contains data important to the programmer.

Variables declared inside of a class should only be accessed by using methods. If there is a variable named **name** within a class named **client**, then the variable can normally be accessed directly:

```
a = client       # Create an instance of client.
print (a.name)
```

This is considered poor form in general. We should have a **get** method for each variable we wish to use, and this method only returns the value of the variable:

```
print (a.get_name())
```

Similarly, we will have a **set** method to assign values to variables within a class:

```
a.set_name("Parker")
```

This protocol makes the class a relatively safe place. Variables can only be accessed and changed through one single method, making it correct if those methods are correct, and making all such accesses easy to locate in the code. For small programs, this matters a lot less than for larger ones, but it is always a good idea to follow this scheme.

A very important method is the *constructor*, which is called automatically by the system when an instance is created. This method is used to set up variables and data structures and perhaps read data at the beginning of some process. Constructors can accept parameters and then save these as local within-class variables. If a class named **client** has a constructor, then it is called whenever an instance is created, and the syntax of the instantiation includes a parameter list even if it is empty:

```
a = client()        # Create an instance of client.
```

The idea is to provide a barrier around the methods and variables in the class. Accesses are controlled, and if the methods in the class are correct and the correct protocol is followed for using **get** and **set** methods, then it will be easier to find problems in the class, and the resulting code should be more reliable and easier to modify.

6.4 CLASSES AS DATA ABSTRACTIONS

We can define a *type* as a *data structure* and a set of *operations* that we commonly perform on that structure. This defines what is called an *abstract data type (ADT)*. This is a formal abstraction for data types, but a class structure can be used as a beginning of practical implementations of types using the model. The underlying variables and data types used in the implementation should only be important to the person implementing the class, and all the user can do is instantiate it and use the operations.

Consider a simple type like Boolean. A Boolean variable can have one of two values, **True** or **False**. These are constants, and their actual values are not important, only that they exist and are always the same. In Python, we could have a statement

```
flag = True
```

and this gives the Boolean variable the value **True**. Using a class to represent a type, we could do the following:

```
flag = Boolean()
flag.set_true()
```

This is more complicated, but shows what is going on. The Boolean constructor establishes an instance of the class Boolean, which is assigned to the variable **flag**. We now assign a value to flag by calling its **set_true** method; there should also be a **set_false**. Now **flag** is a Boolean variable with the value **True.** We can use this in a loop by getting its value through the **get** method:

```
while flag.get():
    . . .
```

Boolean values can have *and*, *or*, and *not* operations applied to them. If we have two Boolean variables, **a** and **b**, then **a and b** is **True** only when both **a** is **True** and **b** is **True**. When implementing a Boolean class we would use a method named **and** to implement this operator:

```
result = a.and(b)
```

The operation **or** would be implemented as a method as well. The **not** operation is *unary*, meaning it operates on only one value. It reverses the truth value. We would not require a parameter for **not**:

```
result.not()
```

A class can have variables inside them, and one special kind is a value that a class defines for programmers to use specifically with that class, usually as a constant. An example could be the values TRUE and FALSE defined as

```
TRUE = 1000
FALSE = 2000
   .  .  .
```

These could be used outside the class as

```
Boolean.TRUE
Boolean.FALSE
```

where the name of the class is Boolean. They must, of course, not be modified after being defined inside the class. Python has not implemented constant variables, but that's what these variables should be.

This implementation is the basis for a Boolean type. Python already has a Boolean type, but the generality of the class construct means we can create our own more complicated types.

6.5 THE PYTHON CLASS – SYNTAX AND SEMANTICS

The "man walks into a bar" example illustrates many aspects of the Python class structure, but obviously omits many details, especially formal ones that can be so important to a programmer. A **class** looks like a function in that there is a keyword, **class**, and a name and a colon, followed by and indented region of code. Everything in that indented region belongs to the class, and cannot be used from outside without using the class name or the name of a variable that is an instance of the class.

The method **__init__** is used to initialize any variables that belong to the class. It is what we called a *constructor* above. Any variables that belong to the class must be accessed through either an instance (from outside of the class) or by using the name **self** (from within the class). **self.name** refers to a variable that was defined inside of the class, whereas simply using **name** refers to a variable local to a method. When **__init__** is called, a set of parameters can be passed and used to initialize variables in the class. If the first parameter is **self**, it means that the method can access class-local variables, otherwise it cannot. Normally, self is passed to **__init__** or it cannot initialize things. Any variable initialized within **__init__** and prefixed by **self** is a class-local variable. Any method that is passed **self** as a parameter can define a new class-local variable, but it makes sense to initialize all of them in one place it that's possible.

A simple example of a class, initialization, and a method is as follows:

```
class person:
    def __init__ (self, name):
        self.name = name

    def introduce (self):
        print ("Hi, my name is ", self.name)

me = person("Jim")
me.introduce()
```

This class has two methods, **__init__()** and **introduce()**. After the class is defined, a variable named **me** is defined and is given a new instance of the **person** class having the name "Jim." Then this variable is used to access the introduce method, which prints the introduction message “Hi, my name is Jim.” A second instance could be created and assigned to a second variable named **you** using

```
you = person ("Mike")
```

and the method call

```
you.introduce()
```

would result in the message “Hi, my name is Mike.” Any number of instances can be created, and some many have the same name as others – they are still distinct instances.

A new class-local variable can be created by any method. In **introduce()**, for example, a new local named **introductions** can be created simply by assigning a value to it.

```
    def introduce (self):
        print ("Hi, my name is ", self.name)
        self.introductions = True
```

This variable is **True** if the method **introductions** has been called. The main program can access this variable directly. If the main program becomes

```
me = person("Jim")
me.introduce()
print (me.introductions)
```

then the program will generate the output

```
Hi, my name is  Jim
True
```

This is the essential information needed to define and use a class in Python.

6.5.1 A Really Simple Class

A common example of a basic class is a point, a place on a plane specified by x and y coordinate. The beginning of this class is

```
class point:
    def __init__ (self, x, y):
        self.x = x
        self.y = y
```

This simply represents the data associated with a mathematical point. What more does it need? Well, two points have a distance between them. A distance method could be added to the point:

```
def distance (self, p):
    d = (self.x-p.x)*(self.x-p.x) + (self.y-p.y)*
        (self.y-p.y)
    return sqrt(d)
```

If a traditional function were to be used to compute distance, it would be written similarly but not identically. It would take two points as parameters:

```
def distance (p1, p2):
    d = (p1.x-p2.x)*(p1.x-p2.x) + (p1.y-p2.y)* (p1.y-p2.y)
   return sqrt(d)
```

The distance method uses one of the points as a preferred parameter, in a sense. The distance between points p1 and p2 would be calculated as

`d = p1.distance(p2)` or `d = p2.distance(p1)`

using the distance method, but as

```
d = distance (p1, p2)
```

if the function was used. To a degree, the difference is a philosophical one. Is *distance* some property that a point has from another point (the method), or is it something that is a thing that is calculated for two things (the function). After a while, it is possible to see the methods and data of a class as belonging to the object, and as somehow being properties of it. That's what makes a class a type definition.

Many object-oriented languages offer the concept of *accessor* methods. Some languages do not allow variables that belong to a class to be used directly, or allow specific controls on access to them. The truth is that having the ability to find the value of variables and to modify them is generally a bad idea. If the only place that a class local variable can be modified is within the class then that limits the places where that can occur, and allows more control over what is possible. Preventing errors in programs is partly a matter of restricting actions to a small region and of knowing exactly what is going on at all times.

Similarly, if some object outside of a class has access to the local variables of that class, then it promotes a dependency on a specific implementation. One of the advantages of an object-oriented implementation is that the interface to the class is fixed and independent of the way that class is implemented. It may seem obvious that a point object has an x, y position and that those would be real numbers, but the point class is the simplest class, and taking advantage of how a class is coded it not always beneficial.

All that an *accessor* method does is return a value of important to a user of a class. The x and y positions are variables local to the class, and many would agree that they should have an *accessor* method:

```
def getx (self):
    return self.x
def gety (self):
    return self.y
```

Rewriting the **distance()** method to use accessor methods changes it only slightly:

```
def distance (self, p):
    d = (self.x-p.getx())*(self.x-p.getx()) +
         (self.y-p.gety())* (self.y-p.gety())
    return sqrt(d)
```

Methods called *mutators* or *setters* are used to modify the value of a variable in a class. They may do more than that, such as checking ranges and types, and tracking modifications.

```
def setx (self, x):
   self.x = x
def sety (self, y):
   self.y = y
```

There are other methods that could be added to even this simple class just in case they were needed, such as to draw the point, to return a string that describes the object, to rotate about the origin or some other point, or to call a *destructor* method when the object is no longer needed. Until it is known what the class will be used for, there may not be any value for this effort, but if a class is being provided for general utility, like the Python *string*, as much functionality would be provided as the programmer's imagination could invent. A draw method could simply print the coordinates, and could be useful for debugging:

```
def draw (self):
    print ("(", self.x, ",", self.y, ") ")
```

Using this class involves creating instances and using the provided methods, and that should be all. A triangle consists of three points. A triangle *class* could be defined as follows:

```
class triangle:
    def __init__ (self, p0, p1, p2):
        self.v0 = p0
        self.v1 = p1
        self.v2 = p2
        self.x = (p0.getx()+p1.getx()+p2.getx())/3
  self.y = (p0.gety()+p1.gety()+p2.gety())/3

    def set_vertices (self, p0, p1, p2):
        self.v0 = p0
        self.v1 = p1
        self.v2 = p2

    def get_vertices (self):
        return ( (self.v0, self.v1, self.v2) )

    def getx (self):
        return self.x

    def gety (self):
        return self.y
```

The (x, y) value of a triangle is its center, or the average value of the x and the y coordinates of the vertices. These are the basic methods. A triangle is likely to be drawn somehow, and the next chapter will explain how to do that. However, without knowing the details, a triangle is a set of lines drawn between the vertices and so might be done that way. As it is, using text only, it will print its vertices:

```
def draw (self):
    print ("Triangle:")
    self.v0.draw()
    self.v1.draw()
    self.v2.draw()
```

The triangle can be moved to a new position. A change in the x and y location specifies the change, and it is done by changing the coordinates of each of the vertices:

```
def move (self, dx, dy)
    coord = p0.getx()
```

```
        p0.setx(coord+dx)
        coord = p0.gety()
        p0.sety(coord+dy)
        coord = p1.getx()
        p1.setx(coord+dx)
        coord = p0.gety()
        p1.sety(coord+dy)
        coord = p2.getx()
        p2.setx(coord+dx)
        coord = p2.gety()
        p2.sety(coord+dy)
        self.x = self.x + dx
        self.y = self.y + dy
```

In this way of expressing things, it is clear that moving the triangle is a matter of changing the coordinates of the vertices. If each point had a **move()** method, then it would be clearer: moving a triangle is a matter of moving each of the vertices:

```
    def move (self, dx, dy):
        p0.move(dx, dy)
        p1.move(dx, dy)
        p2.move(dx, dy)
        self.x = self.x + dx
        self.y = self.y + dy
```

Which of these two **move()** methods seems the best description of what is happening? The more complex are the classes, the more value there is in making an effort to design them to effectively communicate their behaviors and to make things easier to expand and modify. It is also plain that the **move()** method for a point is simpler than that for a triangle. That fact is invisible from outside the class, and it is not relevant.

6.5.2 Encapsulation

In the example of the *point* class, there is no need for an accessor method because the variables can be accessed from outside the class, in spite of the arguments that have been given for more controlled use of these variables. A careful programmer would want to ensure the integrity of classes by forcing the variables to remain protected in some way, and Python allows this while not requiring it.

The variables x and y are accessible and modifiable from outside because of how they are named. Any variable name in a class that begins with an underscore character ('_') cannot be modified by code that does not belong to the class. Such a variable is said to be *protected*. A variable name that begins with two underscore characters cannot be modified or even examined from outside of the class, and is said to be *private*. All other variables are *public*. This applies to method names too, so the method **__init__()** that is the usually constructor is private.

Rewriting the point class to make the internal variables private would be done like this:

```
class point:
  def __init__ (self, x, y):
    self.__x = x
    self.__y = y
  def getx (self):
    return self.__x
  def gety (self):
    return self.__y
  def setx (self, x):
    self.__x = x
  def sety (self, y):
    self.__yy = y
  def distance (self, p):
    d = (self.__x-p.getx())*(self.__x-p.getx()) +
        (self.__y-p.gety())* (self.__y-p.gety())
    return sqrt(d)
  def move(self, dx, dy):
    self.__x = self.__x + dx
    self.__y = self.__y + dy
  def draw (self):
    print ("(", self.__x, ",", self.__y, ") ")
```

Now the internal variables x and y cannot be modified or even have their values examined unless explicitly allowed by a method.

6.6 CLASSES AND DATA TYPES AGAIN

Consider an *integer*. How can it be described so that a person who has not used one before can implement something that looks and acts like an *integer*? This is a specific case of the general problem faced when using computers – to describe a problem in enough detail so that a machine can solve it. The definition could start with the idea that *integers* can be used for counting things. They are numbers that have no fractional part, and that have been extended so that they can be positive or negative.

When designing programs that use classes, it is likely that the classes represent types, although they may not be completely implemented. The design scheme is to sketch a high-level solution and observe what components of that solution behave like types. Those components can be implemented as classes. The remainder of the solution has a structure imposed on it by virtue of the fact that these other types exist and are defined to be used in specific ways. Types can hide their implementation, for example. The underlying nature of an integer does not matter much to a programmer most times, and so it can be hidden behind the class boundary. This has the added feature that it encourages portability: if the implementation has to change, the class can be re-written while providing the same interface to the programmer.

As noted previously, the operations on the type are implemented as methods. The methods can access the internal structure of the class while providing the desired view of the data and ways of manipulating it. The underlying representation of an integer can be unknown to a user of this class. All that is known is the interface, described as methods. If the interface is well documented, then that's all a programmer needs to know. In fact, exposing too much of the class to a programmer can compromise it.

6.6.1 Example: A Deck of Cards

Traditional playing cards have red and black colors, four suits, and a total of 52 cards, 13 in each suit. Individual cards are components of a deck, and can be sorted: a 2 is less than a 3, and a jack less than a king. The ace is a problem: sometimes it is the high card, and sometimes it is the low card. A card possesses the characteristics *suit* and *value*. When playing card games, the cards are dealt from the deck into hands of some number of cards (for example, 13 cards for bridge and 5 for most poker games). The value of a card usually matters. Sometimes cards are compared against each other (poker), sometimes the sum of the values is important (as in blackjack or cribbage), and sometimes the suit matters. These uses of a deck of cards can be used to define how classes are created to implement card games on a computer.

Operations on a card could include to *view* it (it could be face up or face down) and to *compare* it against another card. Comparison operations could include a set of complex specifications to allow for aces being high or low and for some cards having special values (as in spades or baccarat), so a definition step might be very important.

A deck is a collection of cards. There are usually one of each card in a deck, but in some places, such as Las Vegas, there could be four or more complete decks used when playing blackjack. Operations on a deck would include to *shuffle*, to *replace* the entire deck, and to *deal* a card or a hand. With these things in mind, a draft of some Python classes for implementing a card deck can be created:

`class card:`
`   def __init__ (self, face,`
`                 suit):`
`   def value():`
`   def suit():`
`   def facevalue():`
`   def view ():`
`   def compare():`
`   def initialize()`
	`class deck:`
	`    def __init__ (self):`
	`    def deal_card ():`
	`    def deal_hand (ncards):`
	`    def shuffle():`
	`    def replace():`

The way that the methods are implemented depends on the underlying representation. When the programmer calls **deal()**, they expect the method to return a **card**, which is an instance of the card class. How that happens is not relevant to them, but it is relevant to the person who implements the class. In addition, how it happens may be different on different computers, and as long as the result is the same, it does not matter.

For example, a card could be a constant value **r** that represented one of the 52 cards in the deck. The class could contain a set of values for these cards and provide them to programmers as a reference:

```
class card:
    CLUBS_1 = 1
    DIAMONDS_1 = 2
            . . .
```

```
    HEARTS_ACE = 51
    SPADES_ACE = 52

    def __init__ (self, face, suit):
             . . .
```

The variables for the cards, such as CLUBS_1 and DIAMONDS_1, are accessible in all instances of the card class and have the appropriate value. Variables defined in this way have one instance only and are shared by all instances.

A second implementation could be as a tuple. The ace of clubs would be (Clubs, 1), for instance. Each has advantages, but these will not be apparent to the user of the class. For example, the tuple implementation makes it easier to determine the suit of a card. This matters to games that have trump suits. The integer value implementation makes it easier to determine values and do specific comparisons. The value of a card could be stored in a tuple named **ranks**, for example, and **ranks[r]** would be a numerical value associated with the specific card.

6.6.2 A Bouncing Ball

Animations and computer simulations see the world as a set of samples captured at discrete times. An animation, for example, is a set of images of some scene taken at fixed time intervals, generally 1/24th of a second or 1/30th of a second. Simulations use time intervals that are appropriate to the thing being simulated. This example is a simulation and animation of a bouncing ball, first in one dimension and then in two dimensions.

A ball dropped from a height **h** falls to the ground when released. Its speed increases as it falls, because it is being pulled downwards by gravity. The basic equation governing its movement is as follows:

$$\mathbf{s = 1/2at^2 + v_0t} \tag{6.1}$$

where **s** is the distance fallen at time **t**, **v0** is the velocity the object had at time **t=0**, and **a** is the value of the acceleration. For an object at the Earth's surface, the value of **a** is 32 feet/second^2 = 9.8 meters/second^2. For a ball being dropped, **v0** is 0, since it is stationary initially. The distances at successive time intervals of 0.5 seconds are shown in Table 6.2:

Table 6.2
Distances at successive time intervals

Time	S (feet) = 16*t*t	S (meters) = 4.9*t*t
0	0	0
0.5	4	1.225
1	16	4.9
1.5	36	11.025
2	64	19.6
2.5	100	30.625
3	144	44.1

A *class* could be made that would represent a ball. It would have a position and a speed at any given time, and could even be drawn on a computer screen. Making it bounce would be a matter of giving the ball a value that indicated how much of its energy would be lost each time it bounced, meaning that it would eventually stop moving. Writing the code for the class **Ball** could begin with the initialization (the *constructor*):

```
class Ball:
    def __init__(self, height, elasticity):
        self.height = height
        self.e = e
        self.speed = 0.0
        self.a = 32.0
```

This creates and initializes four variables named **height**, **e**, **a**, and **speed** that are local to the class. Remember, the parameter **self** *refers to the class itself*, and any variable that begins with "self." is a part of the class. A variable within the function **__init__** that did not begin with "self." and was not **global** would belong to the function, and would be created and destroyed each time that function was called.

A method (function) that calculates the height of the ball at a specific time is something else that the **Ball** class should provide. This is simply the value of the class local variable height:

```
def height(self):
    return self.height
```

The **self** parameter has to be passed, otherwise the function cannot access the local variable **height**. The simulation needs values of height as a function of time, and time increases in discrete chunks. This could be implemented in several ways: the class could keep track of the time since it was dropped or it could use the time increment to determine the next speed and position. If the former, then a new class variable must be used to store the time; if the latter, then it means it has to be found to increment the speed rather than using total duration. This second idea is simpler than it sounds. The equation of motion **s = 1/2at**2 **+ v**0**t** can use a time increment in place of **t**, and **v**0 is the velocity at the start of the time interval; this yields the new position. The new velocity can be found from a related equation of motion, which is

$$v = at + v_0 \tag{6.2}$$

where **t** is again the time increment and **v**0 is the speed at the beginning of the interval.

The function that updates the speed and position in this manner is called **delta**:

```
def delta (self, dt):
    s = 0.5*self.a*dt*dt + self.speed*dt
    height = height - s
    self.speed = self.speed + self.a*dt
```

Here, the parameter **dt** is the time interval, and so it can be varied to get the position values at various resolutions.

For now, this is the Ball class. Some code is needed to test this class and show how well (or whether) it works, and this is the main part of the program. An instance of Ball has to be created and then the delta method is called repeatedly at time increments of, for an example, 0.1 seconds. A table of height and time can be constructed in this way, and it is a simple matter to see whether the numbers correct. The main program is as follows:

```
b = Ball (12.0,  0.5)
for i in range (0, 20):
    b.delta (0.1)
    print ("At time ", i*0.1, " the ball has fallen to",
          b.height(),  " Feet")
```

The results are what should be expected, showing that this class functions correctly:

```
At time  0.0  the ball has fallen to 12.0  Feet
…
At time  0.5  the ball has fallen to 7.999999999999997  Feet
…
At time  1.0  the ball has fallen to -4.0000000000000036  Feet
…
At time  1.5  the ball has fallen to -24.000000000000004  Feet
…
At time  2.0  the ball has fallen to -52.000000000000014  Feet
…
At time  2.5  the ball has fallen to -88.00000000000003  Feet
…
```

Because the initial height was 12 feet, the distance fallen is 12 minus the value given above (4, 16, 36, 64, and 100 feet), which is in agreement with the initial table for the times listed. It appears to work correctly.

This code does not yet do the bounce, though. When the height reaches 0, the ball is at ground level. It should then *bounce*, begin moving in the reverse direction, with a speed equal to its former downward speed multiplied by the elasticity value. This does not seem challenging until it is realized that the ball is not likely to reach a height of 0 exactly at a time increment's boundary. At one point, the ball will be above 0 and then after the next time unit, the ball will be below 0. When does it actually hit the ground, and where will be the ball actually be at the end of the time increment? This is not a programming issue so much as an algorithmic or mathematical one, but it is a detail that is important to the correctness of the results.

It seems clear that the bounce computation should be performed in the method **delta()**. The height value in the class begins at a positive value and decreases towards 0 as the ball falls. During some specific call to **delta(),** the ball has a positive height at the beginning of the call and a negative one at the end; this means a bounce happened. At that time, the height of the ball is negative. The height of the bounced ball at the end of the time interval is the negated value of the height, so it is positive again, multiplied by the elasticity.

The speed that should be used in the bounce is based not the final speed, but the speed the ball was traveling at the time when the height was 0. This happens when **self.height-s** is zero, or when

```
self.height - s = 0.5*self.a*dt*dt + self.speed*dt
```

Solve this for the time **xt** that makes the equation work out, which is the standard solution to a quadratic equation that is taught in high school:

$$xt = \frac{-\text{self.speed} \pm \sqrt{\text{self.speed}^2 + 2a * \text{self.height}}}{a} \tag{6.3}$$

The value of **xt** is between 0 and **dt**, and is the time within the increment at which the ball struck the ground. At this time the ball will be moving with speed (self.speed + self.a*xt) instead of (self.speed + self.a*dt) for a normal time interval. The ball will reverse direction and reduce speed by the value of elasticity. Now the ball is moving upwards.

The ball is slowed by gravity until it stops on its upward path and drops down again. At the top of the path, its speed is 0; at the beginning of the time interval, the speed is negative, and at the end, it is positive, and that's how the peak is detected. This situation is much simpler than the bounce.

The annotated program is as follows:

```
# Ball.py
import math
class Ball:
# Constructor/initializer
  def __init__(self, height, elasticity):
      self.height = height  # Current height of the ball
      self.e = elasticity   # How much energy is retained each
                            # bounce
      self.speed = 0.0      # Current speed of the ball,
                            # initially 0, down +
      self.a = 32.0         # Acceleration: G= 32 ft/sec^2

# What Java would call an accessor: not really needed.
    def getHeight(self):
        return self.height

# Calculate the new height and speed for a change in time
# of dt seconds.
    def delta (self, dt):
```

```
        startHeight = self.height     # Remember the state before dt
        startSpeed = self.speed
        s = 0.5*self.a*dt*dt + self.speed*dt # Equation 1:
                                             # position update
         self.height = self.height - s
         self.speed = self.speed + self.a*dt  # Equation 2:
                                              # Speed update
         if self.height < 0:   # The sign changed; bounce, when?

     # Equation 3: Solve the quadratic equation to find the
     # time of bounce
             xt = (-startSpeed - math.sqrt(startSpeed*startSpeed
                   +2*self.a*startHeight))/self.a
             if xt < 0:
                 xt = (-startSpeed + math.sqrt(startSpeed*startSpeed
                      +2*self.a*startHeight))/self.a
             print ("Bounces at time ", xt)

# Equation 2 with elasticity
             self.speed = -(self.speed + self.a*xt)*self.e
             self.height = -self.height * self.e     # Correct
                                                     # the height
             if self.e <0.03: self.e = 0.0
             else: self.e = self.e - 0.03

# Peak of the upward bounce, velocity changes sign from + to -
                      # If sign differs then the product is -ve
         elif startSpeed*self.speed < 0:
            self.speed = 0      # Speed is 0 at the top of the bounce
             print("Peak")
         print("New speed is ",self.speed," and height starts at ",
                    self.height)
         if self.height<0.:
             self.height = 0.

b = Ball (12.0,  0.5)  # Initial height 12 feet, elasticity is 0.5
s = Screen (20, 40)

for i in range (0, 50):
    b.delta (0.1)   # Time increment is 0.1 seconds
```

How can this program be effectively tested? The computed values could be compared against hand calculations, but this is time consuming. It was done for a few cases and the simulation was accurate. For this example, another program was written in a different programming language to calculate the same values and the result from the two programs was compared – they were nearly exactly the same. This is not definitive, but is certainly a good indication that this simulation is working properly. In both programs, similar approximations were made, and the numbers agreed to seven decimal places.

6.6.3 Cat-A-Pult

Early in the development of personal computers, a simple game was created that involved shooting cannons. The player would set an angle and a power level and a cannonball would be fired towards the opposing cannon. If the ball struck the cannon, then it would be destroyed, but if not, then the opposing player (or the computer) would fire back at the player's cannon. This process would continue until one or the other cannon was destroyed. This game evolved with time, with more complex graphics, mountainous terrain, and complexity. Its influence can be seen in modern games like *Angry Birds*.

A variation of this game is proposed as an example of how classes can be used. The basic idea is to eliminate a mouse that is eating your garden by firing cats at it; hence the name *cat-a-pult*. The game uses text as input and output, because no graphics facility is available yet. A player types the angle and the power level and the computer fires a cat at the mouse. The location where the cat lands is marked on a simple character display and the player can try again. The goal is to hit the mouse with as few tries as possible.

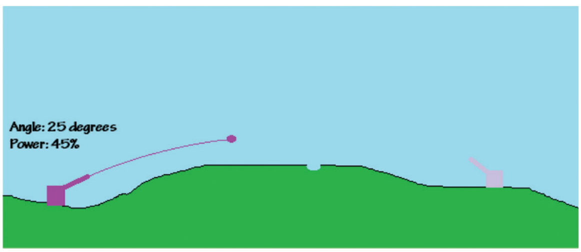


Figure 6.1
Typical configuration of a dueling cannons game.

Basic Design

Before writing any code, one needs to consider the items in this game and the actions they can take. The items are *classes*, and the actions are *methods*. There seem to be two items: a *cannonball* (a cat) and a *cannon*. The target (the mouse) could be a class, too. The cannon has a location, an angle, and a power or force with which the cannonball will be ejected. Both of the last two factors affect the distance the ball travels. The cannon is given a target as a parameter – in this example, the target is another cannon, basically to avoid making yet another class definition.

The action a cannon can perform is to be *fired*. This involves releasing a cannonball with a particular speed and direction from the location of the cannon. In this implementation, an instance of the cannonball class is created when the cannon is fired and is given the angle and velocity as initial parameters; the ball is independent from then on. As a class, the ball has a position (x,y) and a speed (dx, dy). The action that it can perform is to move, which is accomplished using a method named **step()**, and to collide with something, accomplished by the method **testCollision()**.

Detailed Design

In the metaphor of this game, the cannonball is a cat and the target is a mouse, but to the program, these details are not important. Here's what *is* important:

	Class Cannon	**Class Ball**
Has:	position x, y	position x, y
	angle (when fired)	speed dx, dy
	power (when fired)	name (text)
	target (another cannon)	target (a Cannon class instance)
	ball	gravity (force changing the height)
Does:	fire	step
	step	test for collision

All of the *Has* aspects are class local variables, and in this design, they are initialized within the **__init__** method of each class. This would entail the following:

```
self.x = x                  self.x = x
self.y = y                  self.y = y
self.power = 0              self.dx = dx
self.angle = 0              self.dy = dy
self.target = target        self.target = target
self.ball = None            self.gravity = 1.0
                            self.name = ""
```

The game is essentially one-dimensional. The cannonball lands at a specific x coordinate, and if that is near enough to the x coordinate of the target, then the target is destroyed and the game is over. Without a way to draw proper graphics, this can be imagined as a simple text display with the cannon on one side of the screen and the target on the other, something like that seen in Figure 6.1.

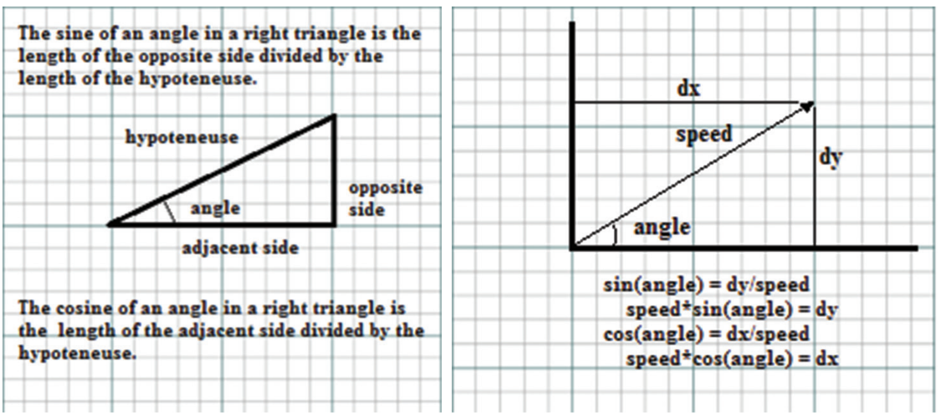
The slash character (/) on the left represents the cannon, and the "Y" represents the mouse, which is the target. The cannon is at horizontal coordinate 12, and the mouse is at 60; both vertical coordinates are 0.

All of the *Does* aspects represent actions, or things the class object can *do*. When the cannon is fired, the ball is created at the cannon coordinates (12, 0) and is given a speed that is related to the angle and power level using trigonometric calculations (Figure 6.2).

```
9 :
8 :
7 :
6 :
5 :
4 :
3 :
2 :
1 :
0 :            /                                               Y
   --------------------------------------------------------------------------------
   01234567890123456789012345678901234567890123456789012345678901234567890
```

Figure 6.2

ASCII (text) video of the game at the beginning.



(a) (b)

Figure 6.3

(a A review of how sines and cosines are computed. (b) Using the definition of sine and cosine to calculate the speed of the ball (or any object) in the x and y directions.

```
dy = sin(angle * 3.1415/180.0)
dx = cos(angle * 3.1415/180.0)
```

The angles passed to **sin** and **cos** must be in radians, so the value PI/180 is used to convert degrees into radians. The coordinates in this case have **y** increasing as the ball moves upwards. When the cannon is fired, a ball is created that has the x and y coordinates of the cannon and the **dx** and **dy** values determined as above. This is accomplished by a method named **fire()**:

Fire: takes an angle and a power

Angle is in degrees, between 0 and 360

Power is between 0 and 100 (a percentage)

1. Compute values for dx and dy from angle and power, where max power is 0.1.
2. Create an instance of Ball giving it x, y, dx, dy, a name ("cat"), and a target (the mouse)

The simulation makes time steps of a fixed duration and calculates positions of objects at the end of that step. Each object should have a method that updates the time by one interval, and it will be named **step()**. The cannon does not move, but sometimes has a cannonball that it has fired, so updating the status of the cannon should update the status of the ball as well:

Step 1: Make one-time step for this object in the simulation. No parameters.

1. If a ball has been fired, then update its position. This is done by calling the **step()** method of the ball.

This defines the cannon.

The ball must also possess a **step**() method, and it will update the ball's position based on its current speed and location. The **x** position is increased by **dx**, and the **y** is increased by **dy**. Gravity pulls down on the ball, effectively decreasing the vertical speed of the ball during each interval. After some trials, it was determined that the value of **dy** should be decreased by the value of **gravity** during each interval. If the ball strikes the ground, it should stop moving. When does this happen? When **y** becomes smaller than 0. When this occurs, set **dx** and **dy** to 0, and check to see if the impact location is near to the target.

Step 2: Make one-time step for this object in the simulation. No parameters.

1. Let x = x + dx, changing the x position.
2. Let y = y + dy, changing the y position.
3. Decrease dy by gravity (dy = dy - gravity)
4. If the ball has struck the ground
5. Let dx = dy = gravity = 0
6. Check for collision with target

Checking to see if the ball hit the target is a matter of looking at the x value of the ball and the x value of the target. If the difference is smaller than some predefined value, say 1.0, then the target was hit. This is determined by a method called **testCollision()**. If the collision occurred, then success has been achieved by the player, so set a flag that ends the game.

testCollision: Check to see if the ball has hit the target, and if so, set a flag to **True**.

1. Subtract the x position of the ball from the x position of the target. Call this **d**.
2. If **d** <= 1.0, then set a flag **done** to **True**.

This defines the class **Ball** and completes the two major classes.

The main program that uses these classes could look something like this:

```
mouse = Cannon (60, 0, None)       # Create the target
player = Cannon (12, 0, mouse)     # create the cannon
player.fire (42, 65)          # Example: fire cannon at
                              # 42 degrees 65% power
done = False                  # initialize variable 'done'
while not done:               # so long as the simulation
                              # is not over
    player.step()             # Update the position of
                              # the ball
```

Actual code for most of this example is shown in Figure 6.4, and the entire program is on the accompanying disk. Included in the disk version is an extra class that draws each state of the game as character graphics that can be displayed in the Python output window; the example in the figure does not include any output, and is unsatisfying to execute The program on the disk generates a numeric and graphical representation of the state, showing the axes, the cannon, the ball, and the target after each step. These can be made into distinct text files and can be made into an animation using *MovieMaker* on a Windows computer or *Final Cut* on a Mac. Such an animation is also included on the disk, and is named *catapult.mp4*.

The process above loosely defines a way to design and code a program that uses classes.

```
from math import *
class Ball:
    def _ _init_ _ (self, x,
                    y, dx, dy,
                    name,
                    other):
      self.xPos = x
      self.yPos = y
      self.xSpeed = dx
      self.ySpeed = dy
      self.gravity = 1.0
        self.name = name
        self.other = other

    def step (self): # One time
                     # step
      self.xPos = self.xPos +
                  self.xSpeed
      self.yPos = self.yPos +
                  self.ySpeed
      self.ySpeed = self.ySpeed
                    - self.
                    gravity
      if self.yPos < 0:
            self.xSpeed = 0
            self.xSpeed = 0
            self.gravity = 0
            self.yPos = 0
            self.testCollision()
```

```
    def testCollision (self):
        global done
        d = self.xPos-self.
                        other.x
        if d<0: d = -d
        if d < 1.0:
            done = True

class Cannon:
    def __init__ (self,  x,  y,
                  other):
      self.x = x
      self.y = y
      self.other = other
      self.ball = None

    def fire (self, angle, pow-
              er):
      dy = sin(angle *
                  3.1415/180.0)
      dx = cos(angle *
                  3.1415/180.0)
      self.ball = Ball(self.x,
                  self.y,
                  dx*power/10.0,
                  dy*power/10.0,
               "Cat", self.other)

    def step (self):
        if self.ball != None:
            (self.ball).step()
```

Figure 6.4
The **Ball** and the **Cannon** classes from the Cat-a-pult simulation.

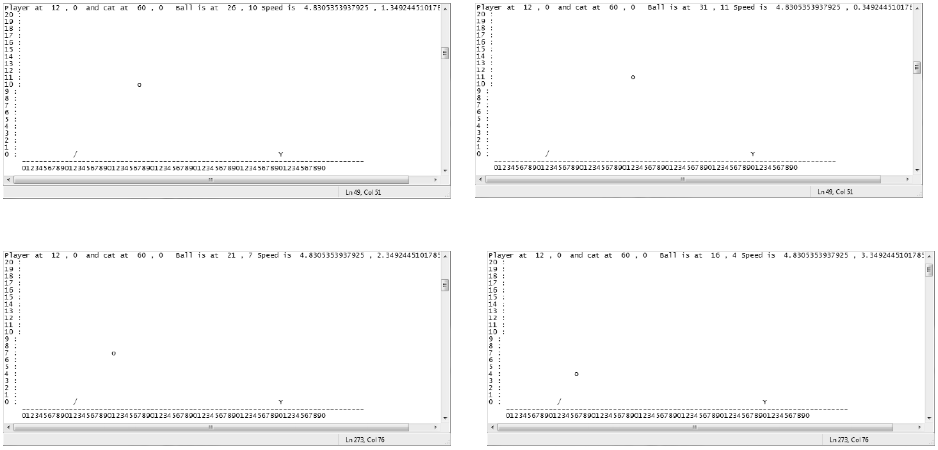


Figure 6.5
Frames from the text animation of the game.

6.7 SUBCLASSES AND INHERITANCE

Classes are designed as language features that can represent a hierarchy of information or structure. A class can be used to define another, and properties from the first class are passed on (inherited) by the other. A class that is based on another in this way is called a *subclass*, and there are many types: a pet class with dogs and cats as special cases; a polygon having triangles and rectangles as subclasses; a *dessert* class, having subclasses *pie*, *cake*, and *cookie*; and even the initial example in this chapter of a man and a woman class and the person class that they can be derived from. A *subclass* is a more specific case of the *superclass (*or *parent* class*)* on which it is based.

The examples above are for explanation, and are not really useful as software components, which begs a question about whether subclasses are really useful things. They are, but it requires non-trivial examples to demonstrate this.

6.7.1 Non-Trivial Example: Objects in a Video Game

To some degree, all objects in a game have some things in common. They are things that can interact with other game objects; they have a position within the volume of space defined by the game and they have a visual appearance. Thus, a description of a class that could implement a game object would include:

```
class gobject:
    position = (0, 0, 0)        # Object position in 3D
    visual = None               # Graphics that represent
                                # the object
    def __init__ (self, pos, vis)
    def getPosition (self):
    def setPosition(self, p):
    def setVisual(self, v):
    def draw (self):
```

Anyone who has played a video game knows that some of the objects can move while others cannot. Objects that move can have their position change, and the position has to be updated regularly. An object that can move can have a speed and a method that updates their position; otherwise it is like a **gobject**. This is a good case for a subclass:

```
class mobject (gobject):
    speed = (0, 0, 0)   # Speed in pixels per frame
                        # the x,y,z directions
    def __init__ (self, s)
    def getSpeed(self):
    def setSpeed(self, s):
    def move(self):
    def collision(self, gobject):
```

The syntax of this has the superclass **gobject** as a parameter (apparently) of the subclass **mobject** being defined. If an instance of a **gobject** is created, its **__init__** method is called and the resulting reference has access to all of the methods in the **gobject** definition, just as one would expect. If an instance of **mobject** is created, the **__init__** method of **mobject** is called, but not that of **gobject**. Nonetheless, all properties and methods of both classes are available through the **mobject** reference. The following is legal:

```
m = mobject ( (12, 0, 0))  # Create mboject with
                           # speed (12,0,0)
m.draw()                   # Draw this object
```

This code is acceptable even though an **mobject** does not possess a method **draw()**; the method defined in the parent class is accessible and will be used.

When the **mobject** is created, it is also a **gobject**, and all of the variables and methods belonging to a **gobject** are defined also. However, the **__init__()** method for **gobject** is not called unless the **mobject __init__()** method does so. This means that, for the **mobject**, the values of **position** and **visual** are not specified by the constructor and will take the default values they were given in the **gobject** class. If no such value was given, they will be undefined, and an error will occur if they are referenced.

Calling the **__init__()** method of the parent class can be done as follows:

```
super().__init__((10,10,10), None)
```

In this instance, the constructor for **gobject** is called, passing a position and a visual. This would normally be done only in the **__init__()** of the subclass.

Now consider the following code. The methods are mainly stubs that print a message, but the output of the program is instructive:

```
    class gobject:
    # Object position in 3D
        position = (0, 0, 0)
    #  Graphics  that  represent
the
    # object
      visual = None
     def __init__ (self,pos,vis):
          self.position = pos
          self.visual = vis
        print ("gobject init")
      def getPosition (self):
          return self.position
         print ("getPosition")
      def setPosition(self, p):
          self.position = p
         print ("setPosition")
      def setVisual(self, v):
          self.visual = v
          print ("setVisual")
      def draw (self):
          print("Draw")
```

```
class mobject (gobject):
# Speed in pixels per frame the
# x,y,z directions
    speed = (0, 0, 0)
    def __init__ (self, s):
        self.speed = s
      super().__init__
             ((10,10,10), None)
        print ("mobject init")
    def getSpeed(self):
        print ("getSpeed")
        return self.speed
    def setSpeed(self, s):
        print ("setSpeed")
        self.speed = s
    def move(self):
        print ("Move")
    def collision(self,
                    gobject):
        print ("collision")

g = gobject ((12, 12,12), None)
m = mobject((13,13,13))
print (m.getPosition())
m.move()
m.draw()
```

The output from this is

gobject init	from the creation of the gobject instance g
gobject init	when m is created it calls the parent __init__
mobject init	from the mobject __init__ when m is created
(10, 10, 10)	m.getPosition, showing access to parent methods
Move	m.move call
Draw	m.draw call, again showing access to parent method

Attempting to call **g.move()** would fail because there is no **move()** method within the **gobject** class. Hence, if an object was passed to a function that would attempt to move it, it would be critical to know whether the parameter passed was a **gobject** or an **mobject**. Consider a method that moves an object **x** out of the path of an **mobject** instance if it can, or changes the path of the **mobject** if it cannot. This method, named **dodge()**, might do the following:

```
def dodge self, (x):
    c = x.getPosition()
    c = c +  (dx, dy, 0)
    x.setPosition (c)
```

However, if the parameter is an instance of a **gobject**, then it should not be moved. The function **isinstance()** can be used to determine this. The result of

```
isinstance (x, gobject)
```

is **True** if x is a **gobject** and **False** otherwise. If **False**, then it cannot be moved and the **dodge()** method will have to move the current **mobject** out of the way instead:

```
def dodge self, (x):
    if isinstance(x, gobject):
        self.position = self.position + (dx, dy, 0)
else:
    c = x.getPosition()
    c = c +  (dx, dy, 0)
    x.setPosition (c)
```

6.8 DUCK TYPING

In many programming languages, types are immutable and compatibility is enforced. This is not generally true in Python, but still there are operations that require specific types. Indexing into a string or tuple must be done using something much like an integer, and not by using a float. Now that classes can be used to build what amounts to new types, more attention should be paid to the things a type should offer and the requirements this puts on a programmer. The fewer restrictions the better, and this is a principle of *duck typing* as well.

It should not really matter what the exact type of the object is that is being manipulated, only that it possesses the properties that are needed. In a very simple case, consider the classes point and triangle that were discussed at the beginning of this chapter. It was proposed that both could have a **draw()** method that would create a graphical representation of these on the screen, and both have a **move()** method, as well. We write a function that moves a *triangle* away from a *point* and draws them both:

```
def moveaway (a, b)
    dx = a.getx()-b.getx()
    dy = a.gety()-d.gety()
    a.move (dx/10, dy/10)
    b.move (-dx/10, -dy/10)
```

Which of the parameters, **a** or **b**, is the *triangle*, and which is the *point*? It does not matter. Both classes have the methods needed by this function, namely **getx()**, **gety()**, and **move()**. Because of this, the calls are symmetrical, and both of the following are the same:

```
moveaway (a, b)
moveaway (b, a)
```

A class that possesses these three methods can be passed to **moveaway()**, and a result will be calculated without error. The essence of duck typing is that, so long as an object offers the service needed (i.e., a method of the correct name and parameter set) to another function or method, then the call is acceptable. There is a way to tell whether the class instance **a** has a **getx()** method: the built-in function **hasattr()**.

```
if hasattr (v1, "getx"):
    x = v1.getx()
```

The first argument is a class instance and the second is the name of the method that is needed, as a string. It returns **True** if the method exists.

(The name *duck typing* comes from the old saying that "if something walks like a duck and quacks like a duck, then it *is* a duck." As long as a class offers the things asked for, then it can be used in that context.)

6.9 SUMMARY

A class, in the general sense, is a template for something that involves data and operations (functions). An object is an instance of a class, a specific instantiation of the template. Defining a class in Python involves specifying a class name and a collection of variables and functions that will belong to that class. A method is a function that belongs to a class, and so can have easy access to its internal data. As a first parameter, a method can be passed the **self** variable by default, which can be thought of as a reference to the object currently executing. Thus, within a method, the expression **self.x** refers to a variable **x** defined in the class. An object is created using the name of the class: for a class named **thing**, an instance **x** is created using **x = thing()**. When this occurs, if there is a method in **thing** named **__init__,** then that method is called. This is referred to as an initializer or a constructor.

Accessing methods in an object is done using dot notation: **obj.method()**. Variables can be accessed in this way, too.

A *subclass* is a class that possesses all of the properties of some other class, the *parent* class or *superclass*, plus some new ones. The data and methods of the parent class can be accessed from the subclass (or *child* class). A subclass of **thing** named **something** would be defined using the syntax:

class something(thing):

A class can represent a new type, where methods represent operations.

Public variables can be accessed and modified from outside of a class; *protected* variables can be accessed but not modified from outside of a class, and must begin with an underscore character (e.g., _variable); *private* variables can neither be accessed nor modified from outside of the class, and must begin with two underscore characters (e.g., __variable).

The principle of *duck typing* is that should not really matter what the exact type of the object is that is being manipulated, only that it possesses the properties that are needed.

Exercises

1. Define a class named *square* in which the construct takes the length of the side as a parameter. This class should have a method **area()** that computes and returns the area of the square.
2. Define a subclass of *square* named *button* that also has a location, passed as X and Y parameters to the constructor. A button always has a width of 10. The button class has the following methods:

   center()   Return the coordinates of the center of the button
   label(s)   Set the value of a text label to be drawn to s

3. Create a class *client*. A client is a data-only class that has no methods other than **__init__()**, but that holds data. In this case the client class holds a **name**, a **category** (retail or commercial), a **time** value (integer) and a **service** value (integer). All values are established when the instance is created by passing parameters to **__init__()**. Now create two subclasses of client, one for each category, *retail* and *commercial*.
4. Define a class named fraction that implements fractional numbers. The constructor takes the numerator and denominator as parameters, and the class provides methods to add, multiply, negate (make negative), print, and find the reciprocal of a fraction. Test this class by calculating the following:

   14/16 * 3/4
   1/2 – 1/4

   Bonus: Reduce the results to the smallest possible denominator.
5. Given the following class

```
class value:
    def __init__ (self)
        self.val = randrange(0,100)
```

   and the initialization

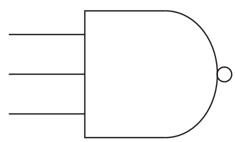
```
        t = ()
        for i in range(0,100):
```

```
v = value()
t = t + (v,)
```

write the code that scans the tuple **t** and locates the smallest integer saved in any of the class instances.

6. Create a class that simulates a NAND logic gate with three inputs. The output will be 1 unless all three inputs are 1, in which case the output is 0. Every time an input is changed, the output is changed to reflect the new state; thus, methods to set each input and to calculate the result will be needed, in addition to a method that returns the output.

Input 1	Input 2	Input 3	Output
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0



Truth table for the 3 input NAND gate and the symbolic representation used in a circuit.

7. A queue is a data structure that accepts new (incoming) data at one end (the back) and stores it in the order of arrival, giving the data at the front of the queue when requested. It's like a line at a cashier in a store: customers wait for the cashier in order of arrival. Implement a queue as a class; it has operations **into()** and **out()** to add items and remove items from the queue, and **empty()** which returns **True** if the queue has no data in it. What is added to the queue are objects of a class *client*, as seen in Exercise 6.3 above.

8. Simulation: The gestation period for a rabbit is 28-32 days, and they will breed a week after having a litter. A female rabbit (a doe) will breed for the first time at about 100 days old. Create a class that represents a rabbit and simulate the growth of a rabbit population that starts with three does at day 0. Assume a litter size of between 3 and 8, and that half of the offspring will be male. Increase time by 1 day at a time and answer the question: "How many rabbits will there be after 1 year?" if the initial population is three females and one male.

Notes and Other Resources

http://www.jesshamrick.com/2011/05/18/an-introduction-to-classes-and-inheritance-in-python/

August 12, 2015. *http://componentsprogramming.com/using-the-right-terms-method/*

Duck typing in Python: *http://www.voidspace.org.uk/python/articles/duck_typing.shtml*

1. R. Chugh, P. Rondon, & R. Jhala (2012, January). *Nested refinements: a logic for duck typing.* In *ACM SIGPLAN Notices* (Vol. 47, No. 1, pp. 231–244). ACM.
2. Ole-Johan Dahl (2002). *The Birth of Object Orientation: the Simula Languages* in *Software Pioneers: Contributions to Software Engineering*, Programming, Software Engineering and Operating Systems Series, Springer. Pp. 79–80.
3. O.-J. Dahl, K. Nygaard: *Class and Subclass Declarations*. In J. Buxton, ed.: *Simulation Programming Languages*. Proceedings from the IFIP Working Conference in Oslo, May 1967. North Holland, 1968.
4. Adele Goldberg and Alan Kay, *Smalltalk-72 Instruction Manual* [page 44]
5. ANSI Smalltalk Standard v1.9 199712 NCITS X3J20 draft, Section 3.1 [page 9].
6. B. Liskov, A Snyder, R. Atkinson, and C. Schaffert (1977). *Abstraction Mechanisms in CLU*. Communications of the ACM 20:8. Pp. 564–576.

CHAPTER 7

GRAPHICS

In this chapter

Since the advent of *Microsoft Windows*, computer graphics have been feature of computers. Before that, graphics were a relatively rare thing, relegated to some research, to a few expensive Hollywood movies, and to science fiction. The first use of 3D computer graphics in a commercial motion picture was in the film *The Andromeda Strain* (1971) (Figure 7.1) in which it was used to show a rotating 3D map (they called it an *electronic diagram*) of the underground installation where the action mainly takes place. A few years later, the film *Westworld* (1973) used 2 ½ minutes of digitally processed video to show the visual perspective of an android. It was a very time-consuming and expensive task at that time; it took about 8 hours to process 10 seconds of film, or about 120 hours in all.

Modern computers all possess fast graphics cards that perform most of the rendering tasks, and these allow for a sophisticated yet simple-to-use graphical/windows interface to desktop computers. Graphics software is hierarchical; the screen itself is merely an array of picture elements (*pixels*) that can be set to any color. It has reached the point where everything seen on a computer screen is actually *drawn* – icons, windows, backgrounds, and even text.

What this means is that interacting with a computer is now done with graphics, not characters and text. Since that is the situation, it makes sense to permit a beginning programmer to experiment with programming graphics applications.

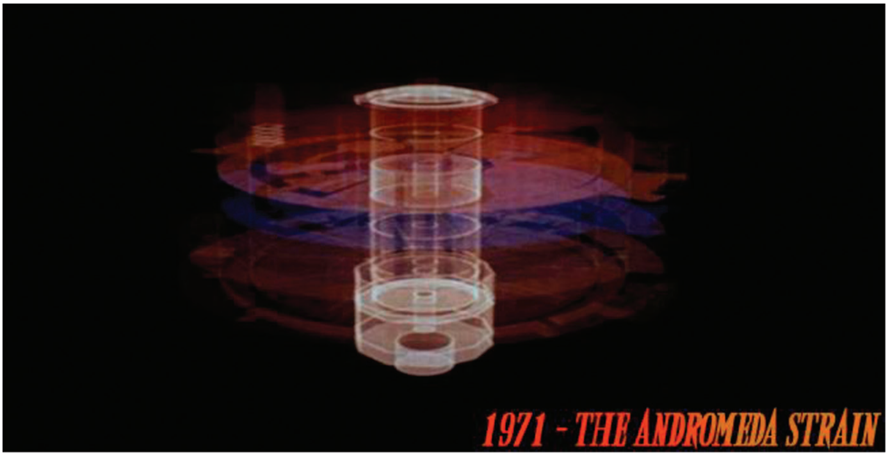


Figure 7.1
A still from the first computer graphic sequence in a major motion picture, The Andromeda Strain (used with permission of the rights holder, MGM).

7.1 INTRODUCTION TO GRAPHICS PROGRAMMING

The most basic aspect of graphics software is the ability to set individual pixels. It is difficult to use this capability to create complex pictures. How is a dog drawn, or a building, or even just a straight line? Those things have been figured out, fortunately.

At the bottom layer of software are functions that manipulate *pixels*. At the next level are *lines* and *curves*; these are the basic components of drawings and sketches. An artist with a pencil uses lines and curves to represent scenes. At the level above lines are functions that use lines to create other objects, such as *rectangles*, *circles*, and *ellipses*. These can be line drawings or can be filled with colors. The next higher levels can be argued about, but text is probably in the next software layer and then shading and images, followed by 3D objects, which includes perspective transformation and textures.

Python does not itself have graphics tools, but various modules that are associated with Python do. The standard graphical user interface library for use with Python is *tkinter*. There are many features of this module, including the creation of windows, drawing, user interface widgets such as buttons, and a host of other features. It is free and is normally included in the Python distribution, but it can easily be downloaded and used with any Python version. Because there are many ways that Python can be configured on various different systems, the installation process will not be described in detail here. A graphics module is included on the disk that accompanies this book; it requires *tkinter*. To build real, complex graphics, we use another module – *Pygame*.

It is essential to install a version of *Pygame* that works with Python 3.

7.2 GRAPHICS IN PYTHON–PYGAME

Using any modern graphics library is a useful exercise in coding. The library provides facilities that the programmer needs, but there is an implicit contract – the programmer has to use the library according to rules devised by its creator. In the case of *Pygame*, a set of initializations is needed, and it asks that you create an *event loop* that repeatedly looks for key presses and mouse clicks (*events*) many times per second. A program cannot predict when a mouse click will happen, so it must be ready at all times to receive one. In the case of Pygame, it breaks up every second into many parts (30 by default) and checks during each interval whether a mouse or keyboard action has taken place. If so, it attempts to alert the programmer by setting a flag that is related to the event. This has consequences for the main program, mainly that it be a loop that repeatedly handles these events. In computer science, this action is called *polling.*

An important aspect of *Pygame* is that it creates a window and manages it. In C++, this can be a complicated proposition, because the operating system does not generally do this for you. Each window on the screen is something managed by a program, which has to figure out how much of the window is visible based on everything else that is on the screen.

7.3 INITIALIZING PYGAME

When using *Pygame*, we first import it as a module:

```
import pygame
```

Then *Pygame* should set up a drawing area in a window. This can be done as follows:

```
screen = pygame.display.set_mode((700, 1000))
```

This code specifically creates a window that is 700 x 1000 pixels and returns a *handle* to it as the variable **screen**. A *handle* is a variable that is used to access the drawing area. In other words, it is the connection to the drawing operations. To draw, we call a *Pygame* function And pass it the drawing area as a parameter, such as **pygame.draw.line(screen, ….).**

Now we can draw things onto the window display surface. They don't show up on the screen right away, though. The system collects the changes to the drawing surface and draws them all at once when the programmer tells it to.

```
pygame.display.update()
```

Now everything that has been drawn to **screen**, it should be displayed. Nothing will be drawn until **update()** is called. The variable **screen** refers to what *Pygame* calls a *Surface*, and is a lot like an image in that it is a collection of rows and columns of pixels. The upper left pixel is the pair of coordinates (0,0), and the first coordinate represents the X or horizontal position.

7.3.1 Colors

To start creating computer graphics, it is necessary to understand how colors and images are represented. When using a computer, everything must be represented as numbers. A pixel is the color of a picture at a particular location, and so there must be a way to describe a color at that place. In physics, *frequency* is used: each color has a specific frequency of electromagnetic radiation. Unfortunately, this does not map very well onto a computer display, because monitors are based on television technology. On a TV, there are three colors, red, green, and blue, and these are used in various proportions to represent every color. There are red, green, and blue dots on the TV screen that are lit up to various degrees to create the colors that are seen. This is based on the way a human eye sees color; there are red, green, and blue sensors in the eye that in combination create our color perception. Another reason that frequency is not used is that there are colors that are not accurately represented as frequencies; they do not appear in the rainbow. The colors pink and brown are two examples.

Each color in the graphics system is represented as the degree of red, green, and blue that combine to create that color. In that sense, it is a bit like mixing paint. Yellow, on a computer, is a mixture of red and green. Each pixel has three components: a red, green, and blue component. These could be expressed as percentages, but when using a computer, it is better to select numbers between 0 and 255 (8 bits or one byte) for each color. Each pixel requires 3 bytes of storage or 4 bytes in some cases, as will be seen shortly. If an image contains 100 rows of 100 pixels, then it has 10,000 pixels and is 10000*3=30000 bytes in size.

To humans, colors have names. Here's a list of some named colors and their RGB equivalents:

Color	Red	Green	Blue	Color	Red	Green	Blue
Black	0	0	0	Olive	128	128	0
White	255	255	255	Khaki	240	230	140
Red	255	0	0	Teal	0	128	128
Green	0	255	0	Sienna	160	83	45
Blue	0	0	255	Tan	210	180	140
Yellow	255	255	0	Indigo	75	0	130
Magenta	255	0	255	Orange	255	165	0

There are, of course, a great many more named colors, and even more colors that can be represented with RGB values in this way (16,777,202 of them, in fact). Each pixel is a color value. All grey values have the special situation R=G=B, so there are 256 distinct values of grey ranging from black to white.

In summary, each pixel represents the color of the image or graphic at that point. A color is represented by the three color components (red, green, and blue), each having a value between 0 and 255. A color is a *tuple*. Thus, (0,0,0) is black, (255,255,255) is white, and (255, 0, 0) is red.

7.4 THE EVENT LOOP

Here is a simple program that displays a drawing created by *Pygame*. Don't worry about the details just now. This program draws a straight line:

```
import pygame
screen = pygame.display.set_mode((1000, 700))
pygame.draw.line(screen, (0,0,0), (10,10), (200,200), 2)
pygame.display.update()
```

The variable screen is initialized, and the line is drawn using the method **pygame.draw.line**. This works, but the program terminates after **update** is called, which closes the window. The line is only on the screen for a tiny fraction of a second. There needs to be a time delay that permits the user to see the result. One way is to place the code inside an infinite loop, and that the program never ends. For example,

```
import pygame
screen = pygame.display.set_mode((1000, 700))
while True:
    pygame.draw.line(screen, (0,0,0), (10,10), (200,200), 2)
     pygame.display.update()
```

Here, the line is drawn and then **update** is repeatedly called within the loop. This means that the line is drawn and the screen is updated many times a second. That's because the program does not end and the window stays open. This solution is unsatisfactory, as it uses CPU cycles for no productive reason, which can slow down the entire computer system. Fortunately, there is a better option. *Pygame* gives us the ability to *wait*, that is, to give up the CPU to other processes, using the *time* class.

Time consists of a set of time related functions, the most useful of which for the purposes here is probably *Clock.tick*. It waits until a specific time interval has passed since the last time *tick* has been called. It has one parameter, which is the number of times per second a tick can occur. Here, the parameter is 1/sec, where sec is the minimum number of seconds of delay is wanted. As a practical example, the loop above could be rewritten to use *tick* as follows:

```
import pygame
import pygame.time
```

```
clock = pygame.time.Clock()
screen = pygame.display.set_mode((1000, 700))
while True:
    clock.tick(10)
    pygame.draw.line(screen, (0,0,0), (10,10), (200,200), 2)
    pygame.display.update()
```

This is very typical of the main loop in a Pygame program. An instance of *Clock* is created (named `clock`) so that *tick* can be called, and it allows the loop to execute 10 times per second. Each call to **tick** ensures that no less than 1/10 of a second has passed since the previous call. We can think of it as meaning "wait until the next clock tick." The behavior is critical for the functioning of a game, which updates the screen every fraction of a second. It is also what will allow the paint program to operate interactively.

To be clear, the use of **tick** allows us to release the CPU and allow other processes on the computer to use it. After at least the period specified has passed, but not necessarily *exactly* that time, the CPU will be given back to the program and it will resume executing.

7.5 DRAWING

Drawing operations that *Pygame* provides are at an intermediate level of complexity. A canvas or *Pygame* **Surface** can draw only pixels. Thus, anything more complicated has to be implemented in terms of the drawing of pixels. Lines, for example, are drawn by drawing pixels that lie on or near to the specified line. The method is referred to as, variously, Digital Differential Analyzer (DDA), scan conversion, or (usually) *Bresenham's* algorithm. It will draw a line between two discrete points by setting pixels between them. While *Pygame* does allow us to set individual pixels, it is not convenient to only use that facility.

So, drawing a line is done using the **line** function in the **draw** package as follows:

```
pygame.draw.line(screen, color, start, end, thick)
```

This draws a line on the *Surface* named **screen** using the specific color, from the start point, a tuple that gives the x and y coordinates of the start point, to the specified end point, specified also as a tuple, with a line thickness of **thick** pixels. Four examples of the use of the **line** function are shown in Figure 7.2.

Drawing a circle is done using the **circle** function in the **draw** package as follows:

```
pygame.draw.circle(screen, color, center, radius, thick)
```

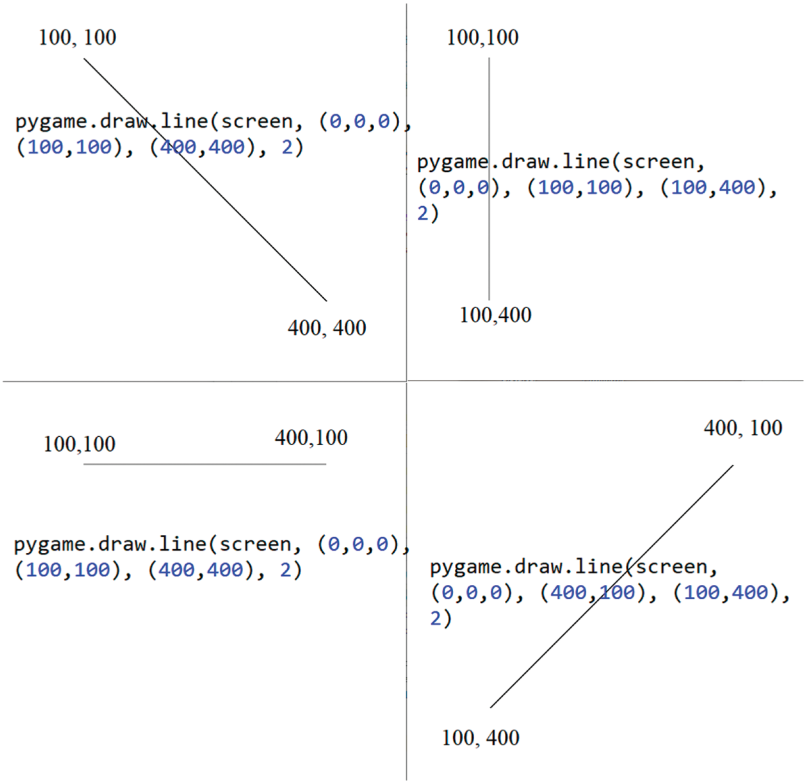


Figure 7.2
Parameters for drawing a line

This draws a circle on the *Surface* named **screen** using the specific color, using the tuple **center** = (x, y) as the coordinates of the center point, and uses the floating point value **radius** as the radius of the circle with a line thickness of **thick** pixels. Color is as before.

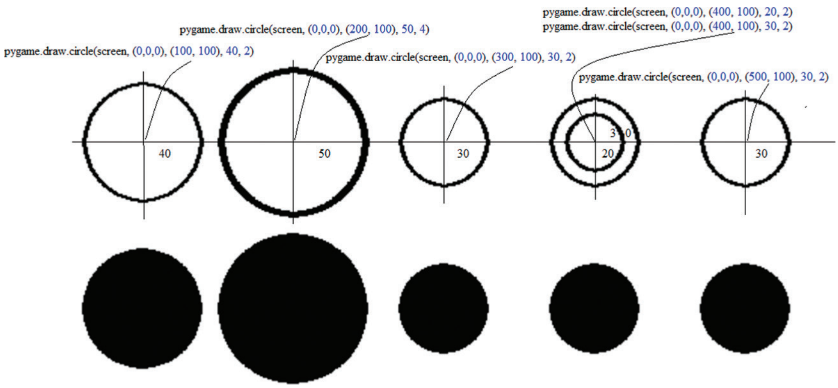


Figure 7.3
Drawing circles.

```
pygame.draw.circle(screen, (0,0,0), (100, 100), 40, 2)
pygame.draw.circle(screen, (0,0,0), (200, 100), 50, 4)
pygame.draw.circle(screen, (0,0,0), (300, 100), 30, 2)
pygame.draw.circle(screen, (0,0,0), (400, 100), 20, 2)
pygame.draw.circle(screen, (0,0,0), (400, 100), 30, 2)
pygame.draw.circle(screen, (0,0,0), (500, 100), 30, 2)

pygame.draw.circle(screen, (0,0,0), (100, 210), 40, 0)
pygame.draw.circle(screen, (0,0,0), (200, 210), 50, 0)
pygame.draw.circle(screen, (0,0,0), (300, 210), 30, 0)
pygame.draw.circle(screen, (0,0,0), (400, 210), 20, 0)
pygame.draw.circle(screen, (0,0,0), (400, 210), 30, 0)
pygame.draw.circle(screen, (0,0,0), (500, 210), 30, 0)
```

This draws the circles seen in Figure 7.3. An important thing to notice is that the second set of six circles is drawn using a thickness of 0. This tells the drawing program to *fill* the circles with the specified fill color. That is also seen in the figure.

Drawing a rectangle is done using the **rect** function in the **draw** package as follows:

```
pygame.draw.rect(screen, color, rectangle, thick)
```

This draws a rectangle on the *Surface* named **screen** using the specific color, using the tuple **rectangle** = (x, y, w, h) as the coordinates of the upper left point (x, y) and the width and height of the rectangle, in pixels (w,h). The circle with a line thickness is **thick** pixels. Again, a thickness of 0 will fill the rectangle. Examples are shown in Figure 7.4.

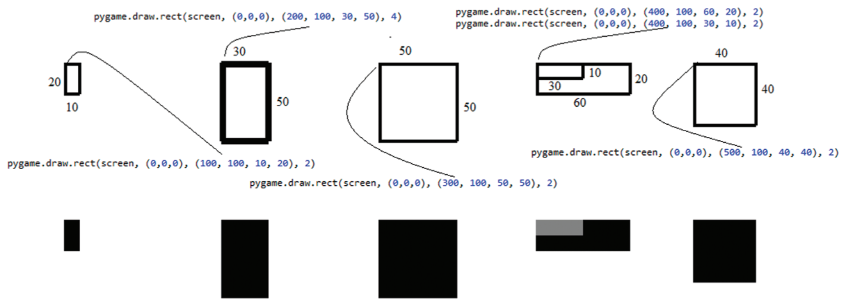


Figure 7.4
Drawing rectangles using Pygame.

Drawing a single pixel is done using the **set_at** function in the **surface** package as follows:

```
screen.set_at((x, y), color)
```

This draws a single pixel on the **screen** surface at the location (x,y) with the color specified by the tuple color.

Example: Create a Page of Note Paper

Note paper has blue lines separated by enough space to write or print text between them. It often has a red vertical line indicating an indentation level, and it serves as a place to begin writing. Drawing this is a matter of drawing a set of connected blue pixels in vertically separated rows, and then making a vertical column of red pixels. Here is one way to code this:

```
import pygame

width = 400
height = 600
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 10

while True:
    clock.tick(FPS)
```

```
    mouseX, mouseY = pygame.mouse.get_pos()
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()

screen.fill((255, 255, 255))
y = 60                                          # Height at which to
                                                # start
for n in range(0, 27):                          # Draw 27 horizontal
                                                # blue lines
    for x in range(0, width):                   # Draw all pixels in
                                                # one line
        screen.set_at((x, y), (0, 0, 255))      # Draw a blue pixel
    y = y + 20                                  # The next line
                                                # is 20 pixels down
for y in range(0, height):                      # Draw connected
                                                # vertical pixels
    screen.set_at((25, y), (255, 0, 0))         # Draw a red pixel
pygame.display.update()
```

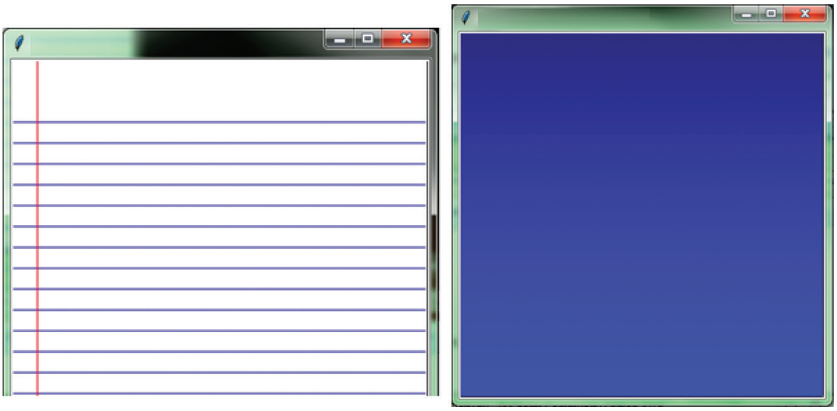
The output of this program is shown in Figure 7.5a. When the pixels are drawn immediately next to each other, they appear to be connected, and so in this case, they form horizontal and vertical lines. This does not easy to do for arbitrary lines; it is not obvious exactly which pixels to fill for a line between, say, (10, 20) and (99, 17). That's why the line drawing functions exist.

Example: Creating a Color Gradient

When creating a visual on a computer, the first step is to have a clear picture of what it will look like. For this example, imagine the sky on a clear day. The horizon shows a lighter blue than the sky directly above, and the color changes continuously all of the way from the horizon to the zenith. If a realistic sky background were needed, then it would be necessary to draw this using the tools available. What would the method be?

First, decide on what the color is at the horizon (**y=ymax**) and at the highest point in the scene **(y=ymin)**. Now ask: "how many pixels between those points?" The change in pixel color will be the color difference from **ymax** to **ymin** divided by the number of pixels. Now simply draw rows of pixels beginning with the horizon and moving up the image (i.e. decreasing Y value) changing the color by this amount each time.

Let's assume that the color at the horizon is blue (40, 40, 255) and the top of the image is a darker blue (40, 40, 128). The height of the image is 400 pixels; the change in blue over that range is 127 units. Thus, the color change over each pixel is going to be 127.0/400, or about 0.32. A color cannot change a fractional amount, of course, but what this means is that the blue value decreases by approximately 1 unit for every 3-pixel-increase in height. Do not forget that the horizon is at the bottom of the image, which has the greatest Y coordinate value, so that an increase in Y means a decrease in height and vice-versa.



(a) (b)

Figure 7.5
(a) A graphic of a sheet of lined paper; (b) a color gradient.

The example program that implements this is as follows:

```
import pygame
width = 400
height = 400
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 10
delta = 127.0/height

while True:
    clock.tick(FPS)
    mouseX, mouseY = pygame.mouse.get_pos()
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
```

```
            quit()

screen.fill((255, 255, 255))
blue = 255
for y in range(0, height):
    yy = height - y
    for x in range(0, width):
        screen.set_at((x, yy), (100, 100, blue))
    blue = blue - delta
pygame.display.update()
```

The gradient image looks like that in 7.5B (a full-color version of this and all images is on the accompanying disk).

7.5.1 Lines and Curves

Straight lines and curves are more complex objects than pixels, consisting of many pixels in an organized arrangement. A line is drawn by setting pixels. The fact that a **line()** function exists means that programmers do not have to figure out what pixels to draw and can focus on the higher level construct: the line or curve.

Example: Note Paper Again

The example of drawing a piece of note paper can be done using lines instead of pixels, and will be a little faster. Set the stroke color to blue and draw a collection of horizontal lines (i.e., that have the same Y coordinate at the endpoints) separated by 20 pixels, as before. Then draw a vertical red line for the margin. The program is a variation on the previous version (only the drawing portion of the code):

```
screen.fill((255, 255, 255))
y = 60                                # Height at which
                                      # to start
for n in range(0, 27):                # Draw 27 horizontal
# blue lines
    for x in range(0, width):         # Draw a blue line
        pygame.draw.line(screen, (0, 0, 255), (0, y),
                                (width, y), 1)
    y = y + 20                        # The next line is 20
                                      # pixels down
for y in range(0, height):            # Draw vertical red line
```

```
pygame.draw.line(screen,  (255,  0,  0),  (25,  0),  (25,
                 height), 1)
pygame.display.update()
```

The output from this program is the same as that for the version that drew pixels, which is shown in Figure 7.5a.

7.6 ARCS AND CURVES

A *curve* is trickier than a line, in that it is harder to specify. The method used in Pygame is like that seen in other common graphics systems: a curve or arc is defined as a portion of an ellipse from a starting angle for a specified number of degrees, as referenced from the center of the ellipse. The angle 0 degrees is horizontal and to the right; 90 degrees is upwards (decreasing Y value). The ellipse is defined by a bounding rectangle, specifying the upper left and lower right coordinates of a box that just holds the ellipse. In Figure 7.6, the rectangle defined by the upper left corner at (100, 50) and the lower right at (300, 200) has a center at (200, 125) and contains an ellipse slightly longer than it is high (upper left of the figure). The function that draws a curve is named **arc()**, and it takes the upper left and lower right coordinates and a starting angle. The size of the arc also expressed as an angle.

In the upper right of the figure, the arc is drawn by the call

```
pygame.draw.arc(screen, (255,0,0), (100,50,300,200),
    math.radians(0), math.radians(90), 2)
```

which means that the part of the ellipse from the 0-degree point *counter clockwise* for 90 degrees will be drawn. The example at the lower left of the figure draws the curve from the 45-degree point for 90 degrees, resulting in the upper section of the ellipse being drawn. The final arc, at the lower right, uses a negative angle. The call

```
pygame.draw.arc(screen, (255,0,0), (100,300,300,200),
    math.radians(-60), math.radians(45), 2)
```

starts at -60 degrees or 300 degrees.

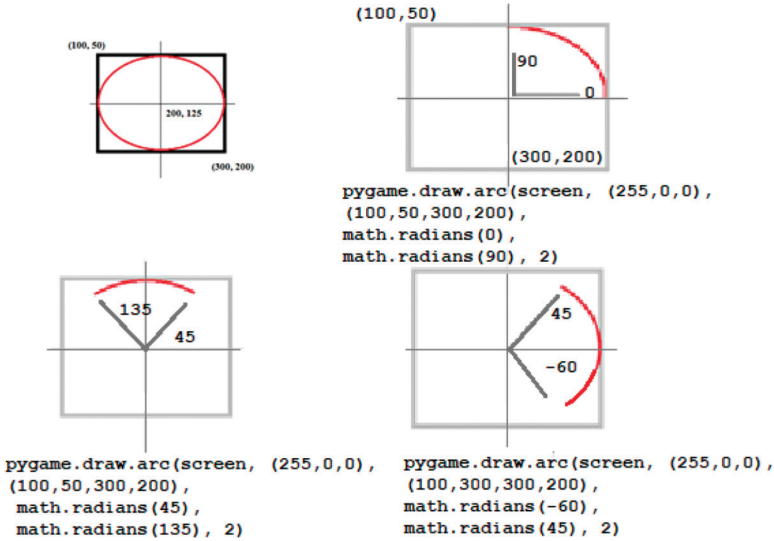


Figure 7.6
The result of calls to the arc function with various parameters. This illustrates how the function can be used.

This way of specifying arcs is fine for simple examples and single curves, but makes combining many arcs into a more complex curve rather difficult. Joining the ends together smoothly is challenging.

The **arc** function has two variations that are important in practice. These possibilities are *chord* and *pieslice*. A chord connects the starting end points of the arc. The call

```
pygame.draw.arc(screen, (255,0,0), (100,300,300,200),
    math.radians(-60), math.radians(45), 2)
```

has a known bounding box and center, but the actual starting and ending points of the arc are not known. Those points are needed to draw both the *pieslice* and *chord*. The equation of an ellipse centered at the point (h,k) is

$$\frac{(x-h)^2}{a^2}+\frac{(y-k)^2}{b^2}=1$$

A better equation for the purposes here is the *parametric* equation, which gives the same curve. It is

$$x = h + a \cos t$$
$$y = k + b \sin t$$

for all values of t from 0 degrees to 360 degrees (0 radians to 2p radians).

In the arc call, the enclosing rectangle is (100,300,300,200), meaning that (100,300) is the upper left corner and (400,500) is the lower right. The center of the ellipse is the center of the bounding box, which is (250,400), so h=250 and k=400 in the ellipse equation.

The value of **a** in the equation is ½ of the width of the bounding box, and b is ½ of the height. In this case, a = width/2 = 150 and b = height/2 = 100. We now know the equation of this ellipse:

$$x = 250 + 150 \cos t$$
$$y = 400 + 100 \sin t$$

The parameter **t** is not the angle from the center to a point on the ellipse, though. It is an angle within a 360-degree circle that defines all points on the ellipse. We can find the start and end points on the ellipse section and either join them with a line (*chord*) or draw lines from each to the ellipse center (*pieslice*)

```
def chord (cx, cy, w, h, a1, a2):
    pygame.draw.arc(screen,
                    (255, 0, 0),
      (cx-w/2, cy-h/2, w, h), a1,
                        a2, 13)
    xs = cx + a*math.cos(-a1)
    ys = cy + b*math.sin(-a1)
    xe = cx + a*math.cos(-a2)
    ye = cy + b*math.sin(-a2)
    pygame.draw.line(screen,
                    (255, 0, 0),
         (xs, ys), (xe, ye), 3)
```

```
def pieslice (cx, cy, w, h,
                  a1, a2):
    pygame.draw.arc(screen,
                    (255, 0, 0),
      (cx-w/2, cy-h/2, w, h), a1,
                        a2, 13)
    xs = cx + a*math.cos(-a1)
    ys = cy + b*math.sin(-a1)
    xe = cx + a*math.cos(-a2)
    ye = cy + b*math.sin(-a2)
    pygame.draw.line(screen,
                    (255, 0, 0),
         (xs, ys), (cx, cy), 3)
    pygame.draw.line(screen,
                    (255, 0, 0),
         (xe, ye), (cx, cy), 3)
```

These functions work a bit differently from **arc**, in that they accept the center coordinates of the ellipse instead of the upper left. Figure 7.4 shows sample output from these functions, and notes a problem. The **arc** function was called specifying a thickness of 4 pixels. The result is not adequate. There are pixels missing within the lines, as if four arcs had been drawn and each was a bit different. This is a minor problem in Pygame.

There is a Pygame function that draws complete ellipses. The code

```
pygame.draw.ellipse(canvas, col, (x, y, w, h), t)
```

draws an ellipse that fits into the bounding box specified using color **col** and line thickness **t**.

7.6.1 Polygons

For the purposes of discussion, a *polygon* includes all closed regions, including ellipses and circles. In that context, the **rect()** function draws axis-oriented rectangular polygons as a special case. A triangle can be drawn using the polygon function:

```
pygame.draw.polygon(screen,(200,100,200),
((350, 350,(50,50), (100,300)))
```

The vertices of the polygon are passed to the function as a tuple (or list) in the third parameter. There is no line thickness given, so the polygon is filled. Any number of vertices can be passed, meaning that we can draw any polygon we like.

Regular polygons are special in that each side of a regular polygon is the same size. Specifying such as thing as a sequence of numerical coordinates can mean a certain amount of time spent with a pencil and graph paper, but it can be done in a general sense. Specify the polygon by giving the coordinates of its center. Specify the size as the distance from the center the center to any vertex, and give the number of sides desired.

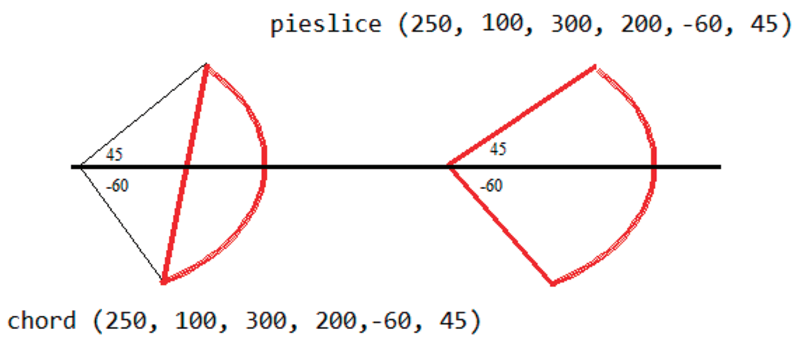
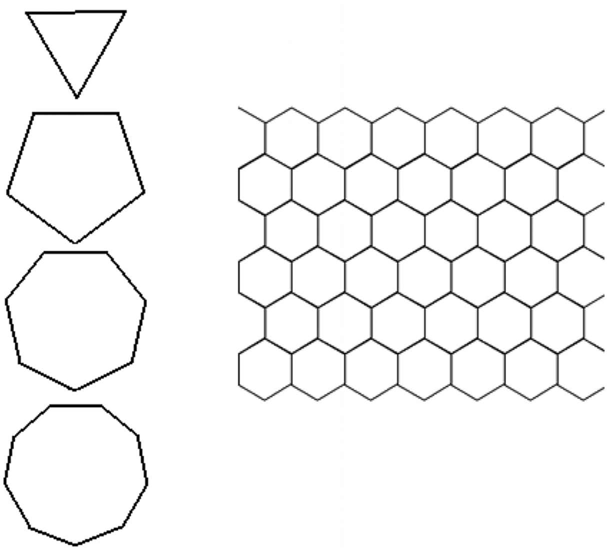


Figure 7.7
A chord (left) and a pie-slice shape (right) drawn using the respective functions.

To draw an arbitrary polygon, split the 360-degree circle into **N** equal angles, where **N** is the number of sides. Find points at a distance R from the center of the circle at each of those angles, where R is the side specified. Now simply connect those points. Basic trigonometry results in the following code:

```
def regular_polygon (xc, yc, r, n):
    pi = 3.1415926
    pi2 = pi/2
    x0 = xc + r
    y0 = yc
    verts = []
    a = 2*pi/n
    for i in range(0,n):
        x0 = xc + math.cos(pi2+a*i) * r
        y0 = yc + math.sin(pi2+a*i) * r
        verts.append([x0,y0])
    pygame.draw.polygon(screen, (0,0,0), verts, 2)
```

Figure 7.8 shows some examples of this function in action, drawing regular polygons and a hexagonal grid.



(a) (b)

Figure 7.8
(a) Regular 3-, 5-, 7-, and 9-sided polygons. (b) A hexagonal grid.

7.6.2 Text

Drawing text more complicated than drawing simpler objects. We need to think about *fonts*. A font is saved on a file and has to be installed on the computer system. If a font is specified by a program but does not exist, then an error will occur, and either the finished image will look different from what was anticipated or an error will occur.

Drawing text is a very specialized operation and consist of three parts:

A graphics rendering class is instantiated and is assigned a font and size.

The text is drawn into a small surface.

The small surface, which is really an image containing the rendered text, is copied to the main display surface at the correct location.

Within Pygame, the module *font* does the loading and rendering of fonts. Specifically, the method Font (*pygame.font.SysFont)* creates a new Font object from a font file on the host computer and provides the needed instance for rendering text. The first parameter is the name of a font as a string, like "Arial" or "Times." If it is None, then the default font is used. The second parameter is the size of the font, in pixels. The Times font at size 14 is specified by the following code:

```
f = pygame.font.SysFont("Times", 14)
```

Now **f** can be used for rendering this specific font and size only. The object returned by *pygame.font.SysFont* has a method named **render** that will return a small image (surface) that has some specified text drawn on it based on the defined font. Rendering the text "Warning" using the variable f above is done by the following:

```
text = f.render("Warning", False, (0,0,0))
```

where the second argument defines whether the text is *antialiased*, and the third argument is the color to be used. The variable **text** is a Pygame *surface* that contains the image of the text. This surface is exactly the right size for the text.

Finally, this text image needs to be copied into the main display surface at the proper location. This introduces a new idea, called *blitting*. Blitting is basically copying one image into another, a pixel by pixel copy from a source to a destination. It is accomplished using a method within the Surface named **blit**. In this precise situation, we want to copy the pixels in the image **text** into the main display surface, which has been named **screen**. So, **screen** is the destination and **text** is the source, and the call is as follows:

```
screen.blit(text, (x, y))
```

where (x,y) specifies where the source image **text** will be drawn within the destination. The tuple (x,y) defines the upper left coordinates in **screen** where the image **text** will be placed.

A simple function that does all of the text drawing stuff is as follows:

```
# Draw a text string at the given point.                **
def text (s, x, y, size=14, f=None):
    global screen
    if f == None:                        # Create a font if needed
        f = pygame.font.SysFont(None, size)
    text = f.render(s, 1, (0,0,0))   # Render the
                                     # string in black
    screen.blit(text, (x, y))
```

This draws the string **s** at location **(x,y)** of the display Surface named **screen**, in black. If a font is passed, then it will be used, otherwise it will create a default font instance, and the size can be specified, or will default to 14 pixels.

7.6.3 Example: A Histogram

A histogram is a way to visualize numerical data. It is especially useful for discrete data like colors or political parties or choices of some kind, but can also be used for continuous data. It displays the counts of something against some other value, such as a category, a percentage of people voting for specific parties, or the heights of grade six girls. It draws bars of various heights each representing the number of entries in each category. In this example the only problem is the plotting of the histogram, but the more general programming problem would include collecting and organizing the data. In this case, the program will read a data file named "histogram.txt" that contains a few key values. The program variable names and the corresponding data file values are as follows:

Variable	Contents
title	Title to be drawn at the top of the graph
ncategories	Number of categories
maxsize	Maximum size of any category

Variable	Contents
hlabel	Horizontal label
vlabel	Vertical label
val[1]	Value for category 1
val[2]	Value for category 2
	…
lab[1]	Label for category 1
lab[2]	Label for category 2
	…

You should design graphical objects carefully. In this case, the histogram has the general appearance shown in Figure 7.9. This visual layout helps with the details of the code, especially if the design has been drawn on graph paper, so that the coordinates can easily be determined.

Assume that the variables needed have been read from the file (see Exercise 2). Here's what the program must do:

Create a window about 600 x 600 pixels in size.
Draw the horizontal and vertical axes (120, 80).
Draw the title and axis labels.

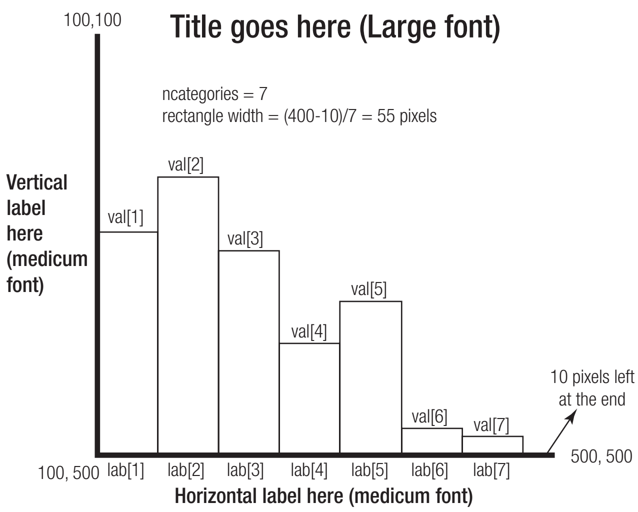


Figure 7.9
The visual design of a histogram before it is coded.

Determine the width and height of each rectangle.

```
For i in range (0, ncategories)
   Draw rectangle i
   Draw label i
```

Development can now proceed according to the plan. Create a window, and set the background. Draw the title and the axes.

```
pygame.draw.line (screen, (0,0,0), (100,100), (100,500), 4)
                                                    # Y Axis
pygame.draw.line (screen, (0,0,0), (100,500), (500,500), 4)
                                                    # X axis
text("Title goes here (large font)", 150, 80, 24, fontt24)
                                                     # Title
```

The horizontal axis label is in a smaller font (14 pixels) at the bottom of the canvas (y-580). It looks nicer if the text is centered. It's challenging to do this exactly without actually drawing the string, so why not do that? In the text function, a Surface is created that is the right size for the string. We can use the width of this surface as the width of the string. A useful function that does this is **textsize**:

```
def textsize (s, size=14, f=None):
    if f == None:                 # Create a font if needed
        f = pygame.font.SysFont(None, size)
    text = f.render(s, 1, (0,0,0))  # Render the string
    x = text.get_size()[0]          # What is the size
                                    # of the Surface?
    return x
```

The only new thing here is the method **get_size()**, which returns a tuple (width, height) that is the size of the Surface object. Now we can center and draw the X axis label:

```
hlabel = "Horizontal label here (medium font)"
cx = (400-textsize(hlabel, 14, fontt14)) / 2
text(hlabel, 100+cx, 530, 14, fontt14)     # Title
```

Drawing the vertical label is more difficult, and so it will be done later. Make it a function:

```
verticalLabel(vlabel)
```

Now, it is time to draw the rectangles. The width of each one is the same, and it is the width of the drawing area divided by the number of categories. The height is the height of the drawing area divided by the maximum value to be drawn, **maxsize**. Compute those values and set the line thickness to one pixel, then set a fill color.

```
wid = (400-10)/ncategories      # Width of a box in pixels
ht = 390.0/maxsize              # Each value is this
                                # many pixels high
```

We then make a loop that draws each rectangle. The X position of a rectangle is its index times the width of a rectangle. The height of the rectangle is the value of that data element multiplied by the variable **ht** that was determined before. We also draw the value being represented at the top of the bar, which is just above and to the right of the rectangle's upper left.

```
for i in range(0,ncategories):
    ulx = 100 + i*wid+2                 # Upper left X
    uly = int(500 - val[i]*ht-0.5)      # Upper left Y (int)
    pygame.draw.rect (screen,  (0,0,0),  (ulx,  uly,  wid,
                      val[i]*ht), 1)
    text (str(val[i]), ulx+15, uly-22, 14, fonth14)
```

The value of the histogram entry is drawn at the top of the rectangle.

Finally, draw the labels for each rectangle. These are below the X axis, centered within the horizontal region for each bin. The labels start at the Y axis (X=100 or so) and their location increased by the width of the bin each iteration of the drawing loop. The Y location is fixed, at 520 – the X axis is 500. Finally, an attempt to center these labels is done in the same way that it was done for the horizontal label, but the parameters are different.

```
x = 100+2
for i in range (0,ncategories):
    cx = wid - textsize(lab[i], 14, fonth14)
    if cx < 0:
        cx = 0
    text (lab[i], x+cx/2, 510)
    x = x + wid
```

Drawing the vertical label involves pulling out the individual words and drawing each one on its own pixel row. Words are separated by spaces (blanks), so one way of drawing the vertical text is to look for a space in the text, draw that word, then move down a few pixels, extract the next word, draw it, and so on, until all words have been drawn. The text is drawn starting at **X=12**, and the initial vertical position is 200, moving down (increasing Y) by 20 pixels for each word. This is done by the function **verticalLabel**(), which is passed the string to be drawn:

```
def verticalLabel(v):
    lasti = 0
    x = 12
    y = 200
    for i in range(0, len(v)): # Look at each character
        if (v[i] == " "):      # Find a space
            text (v[lasti:i], x, y) # Draw the text to
                                     # the space
            y = y + 20               # Increment Y
            lasti = I          # End of his word is start
                               # of next
    text (v[lasti:], x, y)     # Draw
```

This program is available on the disk (gradesHisto.py). The output is shown in Figure 7.10. This is a minimal program, and won't always create a nice image. Labels that are too long and use too many categories can cause badly formatted graphics.

7.6.4 Example: A Pie Chart

A pie chart is really just a histogram where the relative size of the categories is illustrated by an angle instead of the height of a rectangle. Each class is shown as a pie-slice shape of a circle whose area is related to its proportion of the whole sample. Pie-slice-shaped regions are easy to create because we've already written the **pieslice** function. Using the same examples as before, look specifically at the grade data: there are 38 students whose grades are being displayed, and there are 360 degrees in a circle. A category of 10 students, for example (such as those receiving a "B" grade) will represent a pie slice that is 10/38 of the whole circle, or about 95 degrees. The process seems to be to determine how many degrees each category represents and draw a pie slice of that size until the whole pie (circle) is used up.

Create a window about 600 × 600 pixels in size.

Draw the title label.

Establish a fill color.

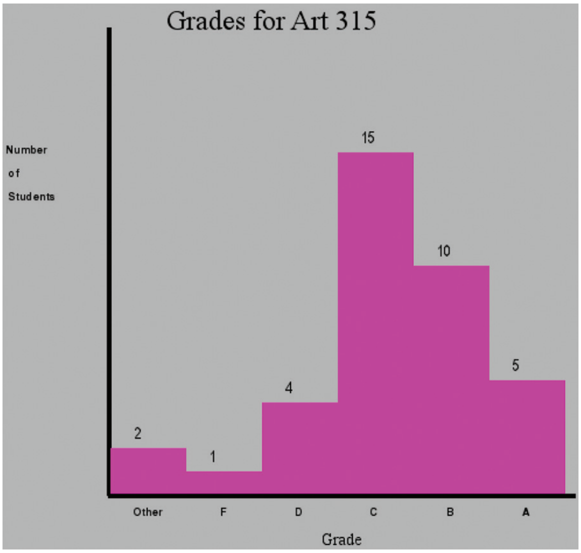


Figure 7.10
Histogram of a set of grades in a university art course.

For i in range (0, ncategories)

Determine the angle A used for this category i.

Draw arc from previous angle for A degrees.

Draw label i for this slice.

Change the fill color.

The labels may present a problem, as they may not fit inside the pie slice. It is probably best to display the label outside of the slice and draw a line to the slice that represents it.

The program is similar to that for the histogram. Beginning after the label is drawn, find the total number of elements in all categories (the number of students in the class). This is the sum of all elements in **val.**

```
totalSize = 0
r = 255
fill (r, 200, 200)
for i in range (0, ncategories):
    totalSize = totalSize + val[i]
```

Each count val[i] in a category represents **val[i]/totalSize** of the entire data set, or the angle **360.0*val[i]/totalSize**. The constant **360/totalSize** is named **anglePerCount**. Now starting at angle 0 degrees, and create a pie-shaped arc the size of each category:

```
span = val[i]*anglePerCount
pieslice(300, 300, 450, 450, angle * conv,
         (angle + span) * conv)
    label (300, 300, 200, lab[i], 1.25,
           angle*conv, (angle+span)*conv)
```

The function **label** draws the text label. The angle to start drawing must be increased so that the next arc starts where this one left off:

```
angle = angle + span
```

Change the color so that each pie piece is a different color. The code below changes the red component just a little.

```
r = r - 20
fill (r, 200, 200)
```

Figure 7.7b shows a way to determine where a label could go; a line from the center of the circle through the outer edge points in the direction of the label. Simply find the x and y coordinates. The y coordinate is the sine of the angle multiplied by the distance from the center, and the x coordinate is the cosine of the angle multiplied by the same distance. For a distance, use the radius multiplied by 1.5. The function **label()** can now be written:

```
def label (xx, yy, r, m, s, a1, ap):
    angle = a1 + ap/2        # Bisector= start angle +
                             # half of span
    d = r*m                  # Distance (m is usually 1.25)
    x = cos (angle* d + xx   # Angle is radians
    text (s, x, y, 20, fonth20)
```

The result is illustrated in Figure 7.11.

There are two more things that could be added to the pie chart program. Sometimes, one of the pieces is moved out of the circle to emphasize it. It turns out that this useful feature can be implemented in a manner very similar to the way the labels were drawn. Find the bisector of the angle for that section and before it is drawn, identify a new center point for that piece a few pixels down

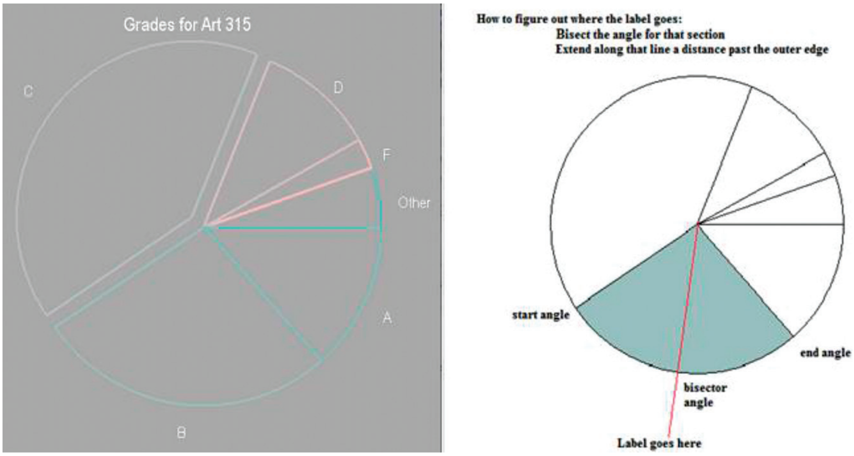


Figure 7.11
(a) The pie chart drawn using Pygame. (b) How to find the placement for labels on the chart.

that bisector. This pulls the piece away from the original circle center. This is the function **pull**.

Next, the pie slices should be *filled* with color, not just outlined. This involves some significant code, because **arc** does not draw thick lines well and does not fill an arc. We'll write our own program to draw filled arcs. Start with the parametric equations for an ellipse:

$$x = h + a \cos t$$
$$y = k + b \sin t$$

Drawing an ellipse means computing x and y for consecutive values of **t** between 0 and 360 degrees (2p radians) and connecting those values by lines. To fill it, use the **pygame.draw.polygon** method to draw the lines as a polygon, and set the line width to 0. To finish this, draw a filled triangle using the center point of the ellipse and the start and end point of the arc.

The code is brief, and is included below for your reference.

```
# Draw a portion of an ellipse
def ell(cx, cy, w, h, a1, a2):
    t = a1
    x0 = cx + w / 2 * cos(-t)
    y0 = cy + h / 2 * sin(-t)
    poly = [(x0, y0)]
    while t < a2:
        t = t + 0.0001
        x1 = cx + w / 2 * cos(-t)
        y1 = cy + h / 2 * sin(-t)
#       pygame.draw.line(screen,
        cf, (x0, y0), (x1, y1), 3)
        x0 = x1
        y0 = y1
        poly.append((x0,y0))
    pygame.draw.polygon (screen,
                         cf, poly)
```

```
def pieslice (cx, cy, w, h, a1,
              a2):
    global cf
    ell(cx, cy, w, h, a1, a2)
    a = b = w/2
    xs = cx + a*cos(-a1)
    ys = cy + b*sin(-a1)
    xe = cx + a*cos(-a2)
    ye = cy + b*sin(-a2)
    pygame.draw.polygon (screen,
cf, ((xs,ys),(cx,cy),(xe,ye)))
#       pygame.draw.line(screen,
cf, (xs, ys), (cx, cy), 4)
#       pygame.draw.line(screen,
cf, (xe, ye), (cx, cy), 4)

def pull (x, y, a1, ap):
    angle = (a1 + ap)/2
    d = 12
    y = -sin (angle) * d + y
    x = cos (angle) * d + x
    pieslice (x-5, y-5, x+150,
              y+150, a1, ap)
```

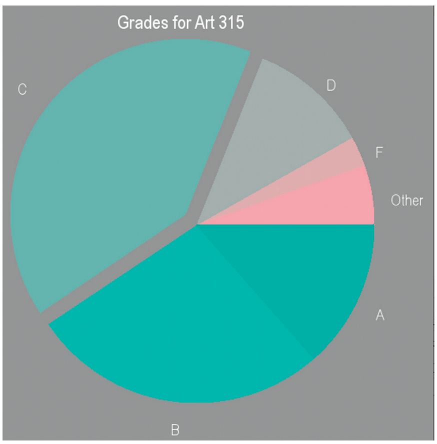


Figure 7.12
The Final Pie Chart, with labels and pull-out section

7.6.5 Images

Unlike the graphical components displayed so far, an *image* is fundamentally a collection of pixels. A camera captures an image and stores it digitally as pixels. Displaying an image means drawing each pixel in the appropriate color, as captured.

Pygame can load and display images in a limited fashion. Images reside in files of various formats, such as JPEG, GIF, BMP, and PNG. The same image in each format is stored in a distinct way, and it can require a lot of code just to get the pixels from the image. Pygame allows image files to be read directly: formats including GIF, PNG, JPG, and BMP are each identified by the last three characters in the file name.

The function **pygame.image.load** will read an image file and return an image as a surface that can be displayed in the graphics window. The file "charlie.gif" is a photo of checkpoint Charlie in Berlin (Figure 7.13), and has been included on the accompanying disk. It could be read in to a Python program with the call:

```
im = pygame.image.load ("charlie.gif")
```

The variable **im** now holds the image, as a *Surface*. We know that a *Surface* has a **get_size** method, and we can now create a display *Surface* and size it to be exactly as large as the image. Displaying the image involves calling the **blit** function. The entire program to read and display this image is as follows:

```
import pygame

im = pygame.image.load ("charlie.gif")
sz = im.get_size()
width = sz[0]
height = sz[1]
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 10
while True:
    clock.tick(FPS)
    if event.type == pygame.QUIT:
        quit()
    screen.fill((180, 180, 180))
    screen.blit(im, (0,0))
    pygame.display.update()
```

A sample result is shown in Figure 7.13.

Figure 7.13
Displayed image of Checkpoint Charlie using Pygame.

Pixels, Again

A Surface is returned by **pygame.image.load**, and as such, we have read and write access to all of the pixels. We can get the value of a pixel in a Surface **im** using **get**:

```
pixel = im.get_at((i,j))
```

where **i** and **j** are the x and y locations of the pixel. The returned value is a color. We can change a value in the Surface using the following code:

```
im.set_at((i,j),c)
```

where c is the color to assign to the pixel at location (i,j). An image consists of rows and columns of pixels, and a pixel is a color. The color components are as follows:

```
red = c[0]
green = c[1]
blue = c[2]
```

These functions operate on an image, but since the main display surface is also of the same type, they apply to it as well.

Example: Identifying a green car

There is a pattern here that is important to recognize when working with images at the pixel level – the raster scan. All of the pixels in the image are examined one at a time using a nested loop. The code is as follows:

```
for i in range(0, width):
    for j in range(0, height):
        # Do something to pixel (i,j)
```

This example uses color to identify the pixels that belong to a car in an image, as seen in Figure 7.10. The problem requires identifying pixels that are green and making them stand out in the image. All pixels have a green component. When something is green, the green component is the most significant one; it is larger than the red and blue components by some margin. In this case, that margin is arbitrarily set at 20 (if it does not work, then it can be modified). If a pixel is green, it will be set to black; otherwise, it will become white; this will make the pixels that belong to the car stand out. The program begins by creating a window and reading in the image:

```
im = pygame.image.load ("eclipse.gif")
sz = im.get_size()
width = sz[0]
height = sz[1]
screen = pygame.display.set_mode((width, height))
```

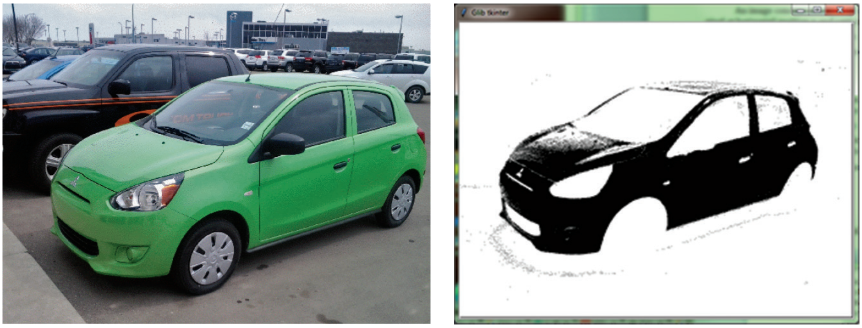
Now look at all of the pixels, searching for a green one:

```
for i in range(0, width):
    for j in range(0, height):
        c = im.get_at((i, j))    # Get the color of the
                                 # pixel (i,j)
```

If the pixel is green, then change it to black. Otherwise, change it to white:

```
if c[1] > (c[0] + 20) and c[1] > (c[2] + 20):
    im.set_at((i, j), (0, 0, 0))
else:
    im.set_at((i, j), (255, 255, 255))
```

Display it and the program is complete (Figure 7.14b). Note that there are some green pixels that do not belong to the car, but most of the car pixels have been identified.



(a) (b)

Figure 7.14
(a) A green car. (b) The result of changing green pixels to black and all others to white.

Example: Thresholding

Image processing is a large subject, and this particular book is not the best choice for exploring it in detail. There are some basic actions that can be done, and common ones include thresholding, edge enhancement, noise reduction, and count, all of which can be done using in Python and drawn using Pygame. Thresholding in particular is an early step in many image-analysis processes. It is the creation of a bi-level image, having just black and white pixels, from a grey or color image. The previous example is different from thresholding in that a particular color was being searched for. In thresholding a simple grey value T, the *threshold*, is used to separate pixels into black and white: all pixels having a value smaller than T will be black, and the others will be white.

We can convert an RGB value to a single grey level by simply averaging the three color components: (red+green+blue)/3. This could be coded as function **grey()**, which converts a color into a simple grey level, which is an integer in the range 0 to 25. The thresholding program begins in the same way as did the previous example. Look at the color of all of the pixels in the image, one at a time:

```
startdraw(640, 480)
im = loadImage ("eclipse.gif")
for i in range(0, Width()):
    for j in range(0, Height()):
        c = getpixel(im, i,j)
```

Figure 7.15
Thresholded green car image

This is the standard scan of all pixels. Now convert the color c to a grey level and compare that against the threshold T=128. Pixels with a grey level below 128 are set to black, the remainder are white:

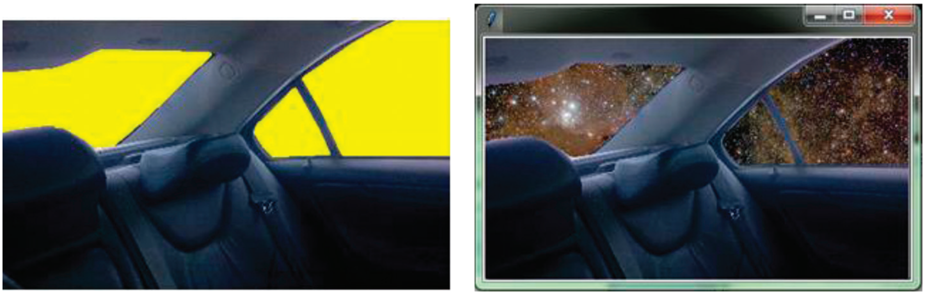
```
for i in range(0, width):
  for j in range(0, height):
      c = im.get_at((i, j))
      g = (c[0]+c[1]+c[2])/3
      if g < T:
          im.set_at((i, j), (0, 0, 0))
      else:
          im.set_at((i, j), (255, 255, 255))
```

The result, the image displayed by this program, is shown in Figure 7.15.

Transparency

A GIF image can have one color chosen to be transparent, meaning that it will not show up and any pixel drawn previously at the same location will be visible. This is very handy in games and animations. Images are rectangular, whereas most objects are not. Consider a small image of a doughnut; the pixels surrounding the donut and in the hole can have the pixels set to be transparent. Then, when the image is drawn, the background will be seen through the hole.

The transparency value must be set within the image by a program. Photoshop, for example, can do this. Then, when Python displays the images, the background image must be displayed first, followed by the images with transparency. As an example, Figure 7.16a shows a photo of the view through the rear and side windows of a Volvo. The window glass area, the places where transparency is desired, is colored yellow. The color yellow was then selected in Photoshop to be transparent, and the image was saved again as a GIF. The short Python program given here can display a background image and the car image over the top of the background, and the background will be seen through the window regions, as shown in Figure 7.16b.



(a) (b)

Figure 7.16
(a An image of a car interior, The window areas have been edited manually to be some color that does not appear in the image otherwise. This color is then set to be transparent by Photoshop or some other editing tool. (b) When the background image is drawn with the car image over the top, the background can be seen through the windows.

```
im = pygame.image.load("../07images/car.gif")     # car image
s  = pygame.image.load("../07images/perseus.gif")
                                            # Background image
sz = im.get_size()
width = sz[0]
height = sz[1]
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 10
while True:
    clock.tick(FPS)
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
    screen.blit(s, (0, 0))
    screen.blit(im, (0, 0))

    pygame.display.update()
```

7.6.6 Generative Art

In *generative art*, artwork is generated by a computer program that uses an algorithm created by the artist. The artist is the creative force, the designer of the visual display, and the computer implements it. There are many generative artists to be found on the Internet: one list can be found online: *http://blog.hvidtfeldts.net/index.php/generative-art-links/*

Much generative art is dynamic: it involves motion and/or interaction, but many works are equivalent to paintings and drawings (*static*). Pygame could be a tool for helping to render these sorts of generative art works. Unlike other sorts of computer programs, those associated with art do not have a known predictable result that can be affirmed as correct. It is true that an artist begins with an idea of what their work should look like and what the message underlying it is, but paintings, sculptures, and generative works rarely finish the way they began.

Either begin with an idea of what the image will look like or describe the idea using a sentence or two. Here's an example sentence: "Imagine a collection of straight lines radiating from a set of randomly placed points within the drawing window, with each set of lines drawn in a saturated strong color."

Now an attempt would be made to create such an image using the functions that Pygame offers. It is often the case that the first few tries are in error, but that one of them is interesting. An artist would pursue the interesting result instead of sticking to the original idea, of course. Here is an example: the code below was written with the idea that it would produce a collection of lines radiating from the point (400,600) from 0 degrees (horizontal right) to 180 degrees (horizontal left) with the color varying slightly:

```
r = 255
for i in range(1, 180, 2):
    pygame.draw.line(screen, (128, r, 128), (x, y),

  (sin(radians(i)) * 500, cos(radians(i)) * 500))
    r = r - 0.5
```

The Y coordinates should have been inverted. Instead, this created a much more interesting image. Sometimes a small error can result in a more interesting result. This is rarely the case when writing scientific or commercial software. The code for one of the other loops in the final code is as follows:

```
x = randrange(100, 800)
y = randrange(100, 500)
r = 255
for i in range(1, 180, 2):
    pygame.draw.line(screen, (r, 200, r), (x, y),
     (sin(radians(-i)) * 500, cos(radians(i)) * 500))
    pygame.draw.line(screen, (r, 200, r), (x, y),
     (sin(radians(i)) * 500, cos(radians(i)) * 500))
    r = r - 0.5
```

This draws some more lines in a nest set of colors from a new location.

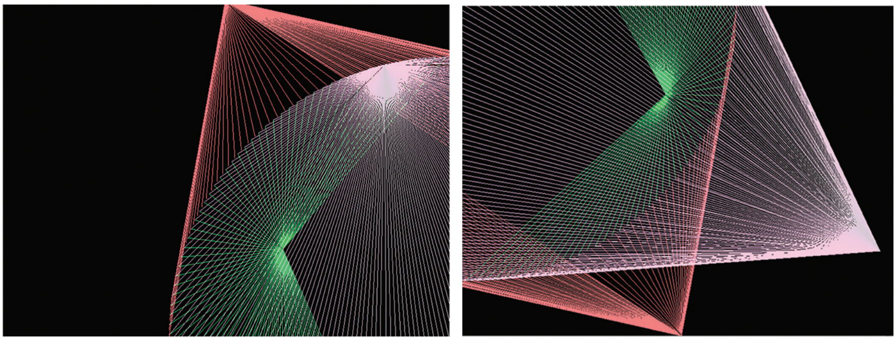


Figure 7.17
Examples of generative art. Colored lines emanate from random points and intersect, creating interesting patterns.

Generative art should be under the control of the artist, but it does use random elements to add interest to the image. In the piece *Snow Boxes* by Noah Larsen, a set of rectangles is drawn, but the specific size and location of these rectangles is random within constrained parameters. The overall color is also random within specified boundaries. Each rectangle is drawn as a collection of white pixels with a density that has been defined specifically for that rectangle so that the image consists of spatters of white pixels that can be identified as rectangular regions (Figure 7.17). Each time the program is executed, a different image is created. The program for *Snow Boxes* was originally written in a language called *Processing*, but a Python version that uses Pygame is:

```
# Snow boxes
# Original by Noah Larsen, @earlatron
```

```
screen.fill ( (randrange(0, 75), randrange(150, 255),
               randrange(0, 75)) )
fill = (255,255,255)
for i in range(0, 10000):
  screen.set_at((randrange(0, width), randrange(0, height)),
                 fill)

for i in range(0, 20):
    xs = randrange(0, width)
    ys = randrange(0, height)
    xe = randrange(xs, xs + randrange(30, 300))
    ye = randrange(ys, ys + randrange(30, 300))

    for j in range(0, 10000):
        screen.set_at( (randrange(xs,xe + 1),
           randrange(ys,ye + 1)) , fill)
```

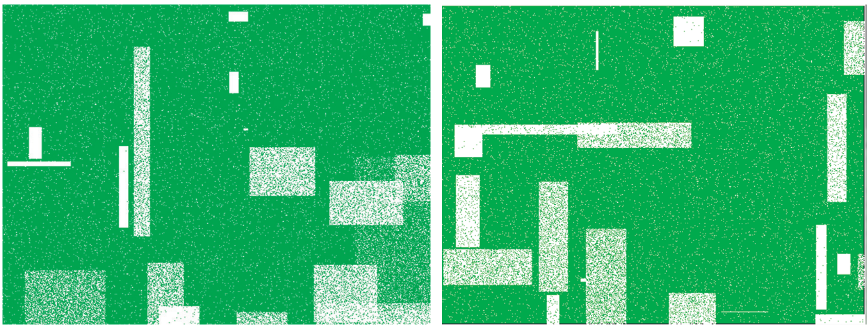


Figure 7.18
Output samples from the Snow Boxes program, examples of generative art.

7.7 SUMMARY

Since the advent of *Windows*, computer graphics have been a feature of computers. Python does not have built-in features for doing graphics, but Pygame does. Drawing is accomplished by setting pixels within a drawing window to a desired color. Colors are specified by giving the amount of red, green, and blue that comprise the color.

Pygame and most graphics libraries allow the user to draw lines, polygons, text, and images, and to set pixels. These basic functions are combined by the programmer to create desired visualizations, such as histograms and pie charts.

Exercises

1. Write a Python program to create the image shown in Figure 7.19a. The image is grey, but the colors that are to be used to fill the circles are given as text. You need not include the text in your output.

2. Draw a set of 10 lines separated horizontally by 20 pixels, each parallel to the line specified by the end points (10, 20) and (200, 421). These lines may begin anywhere in the window.

3. Draw a pyramid using dark grey bricks (rectangles) as components. The base of the pyramid is to be 15 bricks long horizontally, and each successive level is one brick smaller. (Figure 7.19b)

4. Draw a checkerboard. Each square should be 20 x 20 pixels, and the squares are red or yellow, alternating. A checkerboard is 8 x 8 squares.

5. Write a program to draw a visual work in the visual style of Piet Mondrian's famous rectangular compositions, an example of which is shown in Figure 7.19d. Could triangular shapes be used instead of rectangles?

6. Modify the pie chart program so that the data is read from a file named piein.dat.

7. Write a program that reads the file name of an image and displays the image in a window that is correctly sized.

8. The image named "digit.gif" contains some pixels that are pure red; that is, they have a pixel value of (255,0,0). Write a program that locates these pixels, draws a circle around them in a display of the image, and prints their x and y coordinates.

9. An *edge* in an image has the property that the pixel values on one side of the edge are significantly different (i.e., more than 40 levels) from those on the other side. Write a Python program that reads an image and sets pixels at vertical edge locations to black and all other pixels to white; it then displays the result in a window. *Hints*: convert the image to grey or select one color value for the edges. Make a working copy of the image.

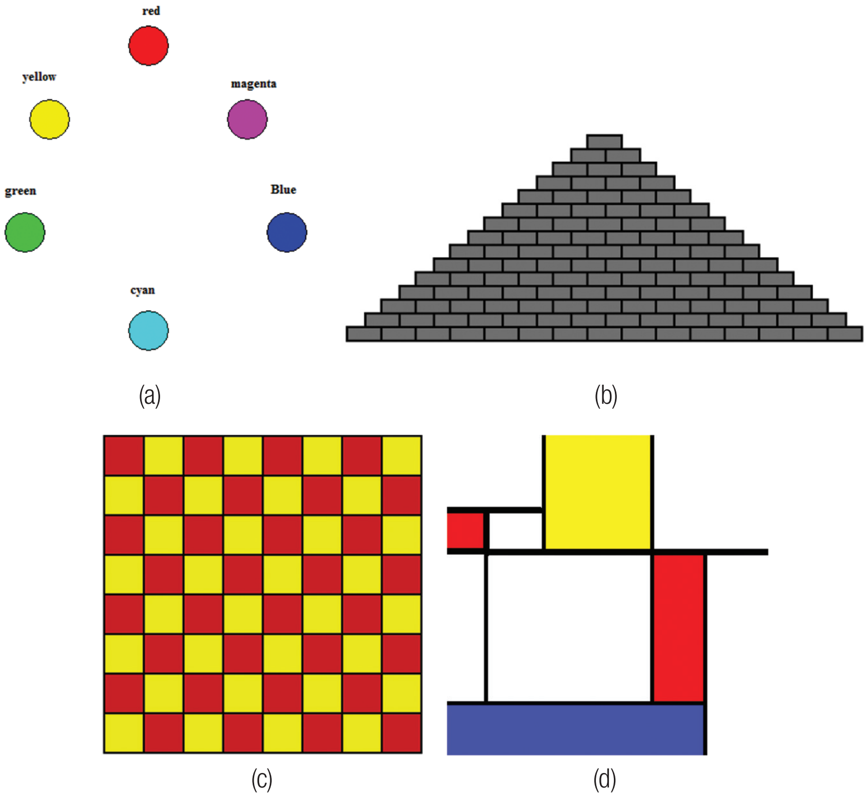


Figure 7.19
Figures to accompany the exercises.

Notes and Other Resources

1. PyGame Tutorial – Game Development Using PyGame in Python, *https://www.edureka.co/blog/pygame-tutorial*
2. Search criteria in IMAP: *http://tools.ietf.org/html/rfc3501#section-6.4.4*
3. Tkinter 8.5 reference. *http://infohost.nmt.edu/tcc/help/pubs/tkinter/web/index.html*
4. *http://www.generativeart.com/*

5. John F. Hughes, Andries van Dam, Morgan McGuire, David F. Sklar, James D. Foley, Steven K. Feiner, Kurt Akeley. (2013) *Computer Graphics: Principles and Practice* (3rd Edition), Addison-Wesley Professional.

6. Robin Landa, Rose Gonnella, Steven Brower. (2006) *2D Visual Basics for Designers,* Delmar Cengage Learning.

7. Jeffrey McConnell, (2005) *Computer Graphics: Theory Into Practice*, Jones & Bartlett Learning.

8. Matt Pearson (2011). *Generative Art.* Manning Publications. ISBN-10: 1935182625.

Chapter 8
Manipulating Data

In this chapter

A fair definition of computer science would be that it is the discipline that concerns itself with information. Computers are an enabling technology, but computer science is largely about how to store, retrieve, represent, compress, display, transmit, and otherwise handle information. Python offers facilities for manipulating information or, at a lower level, data. Data becomes information when a person can interpret it, and information becomes knowledge once understood.

Data on a computer is stored as numbers no matter what its original form was. Computers can only operate using numbers, so an important aspect of using data is the representation of complex ideas as numbers. The manner in which the data is represented as numbers is reflected in the methods used to operate on them.

This chapter is an examination of how certain kinds of data are represented and how computer programs can use data. Python is used for this examination, although some of the discussion deals in generalities. The discussion is driven by how things can be accomplished in a practical way using Python.

Most data consist of measurements of something, and as such, are fundamentally numeric. For example, astronomers measure the brightness of stars and note how they vary as a function of time. The data consists of a collection of numbers that represent the brightness on an arbitrary scale; the units of measurements are always in some sense arbitrary. However, units can be converted from one kind to another, so this is not a problem. Biologists frequently count things, so their data is fundamentally numeric. Social scientists ask questions and collect answers into groups (again a numeric result). What things are not?

Photographs are common enough in science and are not numeric values but are, instead, *visual*; they relate to a human sense that can be understood by other humans easily. Many photographs are analyzed by a computer these days, and there is a way to represent photos digitally. Another human sense that is used to examine data is hearing. Birds sing songs that communicate certain ideas, including what they observe and their willingness to mate. Sounds are vibrations and can indicate problems with machinery, the approach of a vehicle, the presence of a predator, or the current state of the weather. Touch is less often used, but is essential in the control of objects by humans. A person controlling a device at a great distance can profit from the ability to feel the touch of a tool across a computer network.

Then there are search engines, which can be thought of as an extension of human memory and reasoning. The human ability to access information has improved significantly over the past twenty years. If the phrase "Python data manipulation" is entered into the Google search engine, over half a million results are returned.

How is all of this done? It does take some clever algorithms and good programming, but it also requires a language that offers the right facilities.

8.1 DICTIONARIES

A Python *dictionary* is an important structure for dealing with data. One reason is that a dictionary is more properly an advanced structure that is implemented in terms of more basic ones. A *list*, for example, is a collection of things (integers, reals, or strings) that is accessed by using an index, where the index is an integer. If the integer is given, the contents of the list at that location can be retrieved or modified.

A dictionary allows a more complex, expensive, and useful indexing scheme: it is accessed by content (or rather, a description of content). A dictionary can be indexed by a string, which in general would be referred to as a *key*, and the information at that location in the dictionary is said to be *associated* with that key. For example, let's assume we have a dictionary that returns the value of a color given the name. A color, as described in Chapter 7, is specified by a red, green, and blue component. A tuple such as (100,200,100) can be used to represent a color. In a dictionary named **colors**, the value of **colors['red']** is (255,0,0) and **colors['blue']** is (0,0,255). Naturally, it is important to know what names are possible or the index used will not be legal and will cause an error. **colors['copper']** may result in an index error, which is called a *KeyError* for a dictionary.

The Python syntax for setting up a dictionary differs from anything that has been seen before. The dictionary **colors** could be created in this way:

```
colors = {'red':(255, 0, 0), 'blue':(0,0,255),
          'green':(0,255,0)}
```

The braces { … } enclose all of the things being defined as part of the dictionary. Each entry is a pair, with a key followed by a ":" followed by a data element. The pair red:(255,0,0) means that the key "red" is associated with the value (255,0,0) in this dictionary.

Now, the name **colors** looks like a list, but it is indexed by a string:

```
print (colors['blue'])
```

The index is called a *key* when referring to a dictionary. That's because it is not really an index, in that the string cannot directly address a location. Instead, the key is searched for, and if it is a legal key (i.e., it has been defined), the corresponding data element is selected. The definition of **colors** creates a list of keys and a list of data.

Table 8.1
List of keys and data for **colors**

Location	Keys	Data
0	"red"	(255, 0, 0)
1	"blue"	(0, 0, 255)
2	"green"	(0, 255, 0)

When the expression **colors['blue']** is seen, the key "blue" is searched for in the list of all keys. It is found at location 1, so the result of the expression is the data element at 1, which is (0,0,255).

New associations can be made in assignment statements:

```
colors['khaki'] = (240,230,140)
```

A dictionary can be created with an empty pair of braces and then have values given using assignments:

```
colors = {}
colors['red'] = (255, 0, 0)
         .   .   .
```

As with other variables, the value of an element in a dictionary can be changed. This changes the association with the key; there can only be one item associated with a key. The assignment

```
colors['red'] = (200.,0,0)
```

re-assigns the value associated with the key "red." To delete it altogether, use the **del()** function:

```
del(colors['blue'])
```

Other types can be used as keys in a dictionary. In fact, any immutable type can be used. Hence, it is possible to create a dictionary that reverses the association of name to its RGB color, allowing the color to be used as the key and the name to be retrieved. For example,

```
names = {}
names[(255,0,0)] = 'red'
names[(0,255,0)] = 'green'
```

This dictionary uses tuples as keys. Lists cannot be used because they are not immutable.

8.1.1 Example: A Naïve Latin – English Translation

A successful language translation program is difficult to implement. Human languages are unlike computer languages in that they have nuances. Words have more than one meaning, and many words mean essentially the same thing. Some words mean one thing in a particular context and a different thing in another context. Sometimes a word can be a noun and a verb. What this program will do is substitute English words for Latin ones, using a Python dictionary as the basis.

A collection of Latin words with their English counterparts has been placed into a text file named “latin.txt.” The file has the Latin word, a space, and the English equivalent on a single line in the file. The program accepts text from the keyboard and translates it into English, word by word, assuming that it originally consisted of Latin words. The file of Latin words has 3,129 items, but it should be understood that one word in any language has many forms depending on how it is used. Many words are missing in one form or another.

The program is simple. The file of words is read in and converted into a dictionary. The file has a Latin word, a comma, and an English word, so a line is read, converted to a tuple using **split()**, and the Latin word is used as a key to store the English word into the dictionary.

Next, the program asks the user for a phrase in Latin, and the user types it in. The phrase is split into individual words. Each word is looked up in the dictionary, and the English version is printed. This is the first step in creating a translation program. The code looks like this:

```
def load_words (name, dict):  # Read the file of words
  f = open (name, "r")
  s = f.readline()            # Read one word pair
  while s != "":              # exit when the file has been
                              # read
        c = s.split (",")     # Split at the comma
        if len(c)<2:          # Possible error: no words?
            s = f.readline()  # Read next and continue
            continue
        sw = c[0].strip()     # Get the latin and
                              # English words.
        ew = c[1].strip()
        if len(ew) <=0:       # OK?
            s = f.readline()  # Nope. Just skip it.
            continue
        if ew[-1] == "\n":    # Get ride of the endline
            ew = ew[0:-2]
        dict[sw] = ew         # Place in dictionary
        s = f.readline()      # Next word pair from the
                              # file
```

```
    f.close()                  # Always close when done

dict = {}
load_words("latin.txt", dict)  # Read all of the word pairs

inp = input("Enter a latin phrase ") # Get the Latin text
while inp != "":                     # Done?
    book = inp.split(" ")            # Split at words
    for i in range(0,len(book)):     # For each word this
                                     # line
        sword = book[i].lower()      # Lower case
        try:
            enword = dict[sword]     # Look up Latin word
            print (enword, end="")   # Print English
                                     # version
        except:
            print (sword, end="")    # Latin not in
                                     # dictionary
        print (" ", end="")          # Print the Latin
    print (".")
    inp = input("Enter a latin phrase ") # Do it again
```

Translation is more complex than just changing words, and that's all this program does. Still, it is an important step. A favorite Latin phrase from the TV program *The West Wing* is "Post hoc, ergo propter hoc." Given this phrase, the program produced

after this therefore because of this.

which is a good translation. The phrase "All dogs go to heaven" was sent to an online translation program, which produced

omnes canes ad caelum ire conspexerit

This program here translates it back into English as:

all dogs to sky go conspexerit

The word "conspexerit" was not successfully translated, so it was left as it was (the online program translates that word as "glance").

However, the program does not perform well on the Lord's Prayer:

Pater noster qui es in caelis sanctificetur nomen tuum.

Adveniat regnum tuum.

Fiat voluntas tua sicut in caelo et in terra.

Panem nostrum quotidianum da nobis hodie et dimitte nobis debita nostra sicut et nos dimittimus debitoribus.

Fiat voluntas tua sicut in caelo et in terra.

Amen

The above Latin version was turned into the following English translation:

father our that you are against heavens holy name your

down rule your

becomes last your as against heaven and against earth

bread our daily da us day and dimitte us debita our as and us forgive debtors

becomes last your as in heaven and in earth

amen

A useful addition to the code would be to permit the user to add new words into the dictionary. In particular, it could prompt the user for words that it could not find, and perhaps even ask whether similar words were related to the unknown one, such as "dimittimus" and "dimitte." (Being able to have a basic understanding of the grammar would be better still.)

8.1.2 Functions for Dictionaries

The power of the store-fetch scheme in the dictionary is impressive. There are some methods that apply mainly to dictionaries and that can be useful in more complex programs. The method **keys()** returns the collection of all of the keys that can be used with a dictionary. So

```
list(dict.keys())
```

is a list of all of the keys, and this can be searched before doing any complex operations on the dictionary. The list of keys is not in any specific order, and if they need to be sorted then

```
sorted(dict.keys())
```

will do the job. The **del()** method has been used to remove specific keys, but **dict.clear()** removes all of them.

The method **setdefault()** can establish a default value for a key that has not been defined. When an attempt is made to access a dictionary using a key, an error occurs if the key has not been defined for that dictionary. This method makes the key known so that no error will occur and a value can be returned for it (**None**, perhaps).

```
dict.setdefault(key, default=None)
```

Other useful functions include:

dict.copy()	returns a (shallow) copy of the dictionary
dict.fromkeys()	creates a new dictionary setting keys and values; e.g., dict.fromkeys(("one," "two"), 3) creates {("one," 3), ("two," 3)}
dict.items()	returns a list of *dict*'s (key, value) tuple pairs
dict.values()	returns list of dictionary *dict*'s values
dict.update(dict2)	adds the key-value pairs from dictionary dict2 to dict

The expression **key in dict** is True if the key specified exists in the dictionary dict.

8.1.3 Dictionaries and Loops

Dictionaries are intended for random access, but on occasion, it is necessary to scan through parts or all of one. We need to create a list from the pairs in the dictionary and then loop through the list. For example,

```
for (key,value) in dict.items():
    print (key, " has the value ", value)
```

The keys are given in an internal order, which is not alphabetical. It is a simple matter to sort them, though:

```
for (key,value) in sorted(dict.items()):
    print (key, " has the value ", value)
```

By converting the dictionary pairs in a list, any of the operations on lists can be applied to a dictionary as well. It is even possible to use comprehensions to initialize a dictionary. For example

```
d = {angle:sin(radians(angle)) for angle in (0,45.,90.,
     135., 180.)}
```

creates a dictionary of the sines of some angles indexed by the angle.

8.2 ARRAYS

For programmers who have used other languages, Python *lists* have many of the properties of an *array*, which in C++ or Java is a collection of consecutive memory locations that contain the same type of value. *Lists* may be designed to make operations such as concatenation efficient, which means that a *list* may not be the most efficient way to store things. A Python *array* is a class that mimics the array type of other languages and offers efficiency in storage, exchanging that for flexibility.

Only certain types can be stored in an array, and the type of the array is specified when it is created. For example,

```
data = array('f', [12.8, 5.4, 8.0, 8.0, 9.21, 3.14])
```

creates an array of 6 floating point numbers; the type is indicated by the "f" as the first parameter to the constructor. This concept is unlike the Python norm of types being dynamic and malleable. An *array* is an array of one kind of thing, and an *array* can only hold a restricted set of types.

The type code, the first parameter to the constructor, can have one of 13 values, but the most commonly used ones are as follows:

'b' C++ char type

'B' C++ unsigned char type

'i': C++ int type

'l': C++ long type

'f': C++ float type

'd': C++ double type

Arrays are class objects and are provided in the built-in module *array*, which must be imported:

```
from array import array
```

An *array* is a sequence type, and it has the basic properties and operations that Python provides for all the sequence types. Array elements can be assigned to and can be used in expressions, and arrays can be searched and extended like other sequences. There are some features of arrays that are unique:

frombytes (s) The string argument **s** is converted into byte sequences and appended to the array.

fromfile(f, num)	Read **num** items from the file object **f** and append them. An integer, for example, is one item.
fromlist (x)	Append the elements from the list x to the array.
tobytes()	Convert the array into a sequence of bytes in machine representation.
tofile(f)	Write the array as a sequence of bytes to the file **f**.

In most cases, arrays are used to speed up numerical operations, but they can also be used to access the underlying representations of numbers.

8.3 FORMATTED TEXT, FORMATTED I/O

There is a generally believed theory that if numbers line up in nice columns, then they must be correct. This is obviously not true, but appearances can matter a great deal, and numbers that do *not* line up properly for easy reading look sloppy and give people the impression that they may not be as carefully prepared as they should have been. The Python **print()** function as used so far prints a collection of variables and constants with no real attention to a format. Each item is printed in the order specified with a space between the items. Sometimes that's good enough.

The Python versions since 2.7 have incorporated a string **format()** method that allows a programmer to specify how values should be placed within a string. The idea is to create a string that contains the formatted output, and then print the string. A simple example is as follows:

```
s = "x={} y={}"
fs = s.format (121.2, 6)
```

The string **fs** now contains "x=121.2 y=6." The braces within the format string **s** hold the place for a value. The **format**() method lists values to be placed into the string, and with no other information given, it does so in order of appearance (in this case, 121.2 followed by 6). The first pair of braces is replaced by the first value, 121.2, and the second pair of braces is replaced by the second value, which is 6. Now the string **fs** can be printed.

This is not how it is usually done, though. Because this is usually part of the output process, it is often placed within the **print()** call:

```
print ("x={} y={}".format(121.2, 6) )
```

where the **format()** method is referenced from the string constant. No actual formatting is done by this particular call, merely a conversion to string and a substitution of values. The way formatting is done depends on the type of the value being formatted, the most common types being strings, integers, and floats.

8.3.1 Example: NASA Meteorite Landing Data

NASA publishes a large amount of data on its websites, and one of these is a collection of meteorite landings. It covers many years and has over 4,800 entries. The task assigned here is to print a nicely formatted report on selected parts of the data. The data on the file has its fields separated by commas, and there are ten of them: name, id, nametype, recclass, mass, Fall, year, reclat, reclong, and GeoLocation. The report requires that the name, recclass, mass, reclat, and reclong be arranged in a nicely formatted set of columns.

Reading the data involves opening the file, which is named "met.txt," calling **readline()**, and then creating a list of the fields using **split(",")**. If this is done and the fields are printed using **print()**, the result is messy. An abbreviated example is as follows (simulated data here):

```
infile = open ("met.txt", "r")
inline = infile.readline()

while inline !="":
    inlist = inline.split(",")
    mass = float(inlist[4])
    lat =  float(inlist[7])
    long = float(inlist[8])
    print (inlist[0], inlist[3], inlist[4], inlist[7],
           inlist[8])
    inline = infile.readline()
infile.close()
```

The result is, as predicted, messy:

```
Ashdon H5 121.13519985254874 89.85924301385958
       -126.27404435776049
Arbol Solo H6 66.94777134343516 25.567048824444797
           160.58088365396014
Baldwyn L6 47.6388587105465 -7.708508536783924
        -81.22266156597777
```

```
Ankober L6 15.265523451122064 -32.01862330869428
        102.31244557598723
Ankober LL6 57.584802700693885 -84.85880091616322
        106.31130649523368
Ash Creek L6 62.130089525516155 76.02832670618457
          -140.03422105516938
Almahata Sitta LL5 30.476879105555653 -12.906745404586
               47.411816322674
```

Nothing lines up in columns, and the numbers show an impossible degree of precision. There are also no headings.

The first field printed is called *name*, and is a string; it is the name of the location where the observation was made. The print statement simply adds a space after printing it, and so the next thing is printed immediately following it. Things do not line up. Formatting a string for output involves specifying how much space to allow and whether the string should be centered or aligned to the left or right side of the area where it will be printed. Applying a left alignment to the string variable named **placename** in a field of 16 characters would be done as follows:

```
'{:16s}'.format(placename)
```

The braces, which have previously been empty, contain formatting directives. Empty braces mean *no formatting*, and simply hold the place for a value. A full format could contain a name, a conversion part, and a specification:

{ [name] ['!' conversion] [':' specification] }

where optional parts are in square brackets. Thus, the minimal format specification is '{}.' In the example "{:16s}," there is no name and no conversion parts, only a specification. After the ":" is "16s," meaning that the data to be placed here is a string, and that 16 characters should be allowed for it. It will be left aligned by default, so if **placename** was "Atlanta," the result of the formatting would be the string "Atlanta   ," left aligned in a 16-character string. Unfortunately, if the original string is longer than 16 characters, it will not be truncated, and all of the characters will be placed in the resulting string, even if it makes it too long.

To right align a string, place a ">" character immediately following the ":". So

```
"{:>16s}".format("Atlanta")
```

results in "   Atlanta." Placing a "<" character there does a left alignment (the default) and "^" means to center it in the available space. The alignment specifications apply to numbers as well as strings.

The first two values to be printed in the example are the city name, which is in **inlist[0]**, and the meteorite class, which is **inlist[3]**. Formatting these is done as follows:

```
s = '{:16s} {:10s}'.format(inlist[0], inlist[3])
```

Both strings are left aligned.

Numeric formats are more complicated. For integers, there is the total space to allow, and also how to align it and what to do with the sign and leading zeros. The formatting letter for an integer is "d," so Table 8.2 shows the legal directives and their meanings.

Table 8.2
Numeric formats

Format	Explanation	Result for value 1234
'{:5d}'	An integer in a 5-character space, right aligned	" 1234"
'{:>5d}'	An integer in a 5-character space, right aligned	" 1234"
'{:<7d}"	An integer in a 7-character space, left aligned	"1234 "
'{:07d}'	An integer right aligned in a 7-character space filled on the left with zeros.	"0001234"
'{:,7d}'	A right aligned integer in a 7-character space with a ',' every 3 digits	" 1,234"
'{:7x}'	A right aligned integer in hexadecimal.	" 4D2"

Floating point numbers have the extra issue of the decimal place. The format character is often "f," but it can be "e" for exponential format or "g" for general format, meaning the system decides whether to use "f" or "e." Otherwise, the formatting of a floating point number is like that of previous versions of Python and like that of C and C++.

Table 8.2
Floating point number formats

Format	Explanation	Result for value 12.321
'{:.3f}'	3 digits right of the decimal	'12.321'
'{:6.2f}'	6 digits, 3 to the right of the decimal	' 12.32'
'{:>8.1}'	5 digits, 1 to the right, left adjusted	' 12.3'
'{:8e}'	8 places, exponential form	**'1.232100e+01'**
'{:8g}'	8 places, system decides	**' 12.321'**

The next three values that are printed are floating points: the mass of the meteorite and the location, as the latitude and longitude. We print each of these as 7 places, 2 to the right of the decimal ('{:7.2f}').

The solution to the problem is as follows. The data is read line by line, converted into a list, and then the fields are formatted and printed in two steps:

```
infile = open ("met.txt", "r")
inline = infile.readline()
print ("    Place     Class    Mass   Latitude  Longitude")
while inline !="":
    inlist = inline.split(",")
    mass = float(inlist[4])
    lat =  float(inlist[7])
    long = float(inlist[8])
    print('{:16s} {:14s} {:7.2f}'.format(inlist[0],
                              inlist[3],mass),end="")
    print ('  {:7.2f}     {:7.2f}'.format(lat, long))
    inline = infile.readline()
infile.close()
```

The results are as follows:

```
Place                Class            Mass        Latitude     Longitude
Bloomington  L5                      13.58          9.53       -150.85
Bogou        LL6                    121.09        -66.28        -53.08
Alessandria  L4                     106.11         63.68         10.96
Bo Xian      L5                      85.92          0.33        -50.28
Ashdon       Eucrite-mmict            6.59        -88.22       -178.84
Berduc       L6                     111.76        -64.20        107.10
...
```

There are many more formatting directives and a large number of combinations.

8.4 ADVANCED DATA FILES

File operations were discussed Chapter 5, but the discussion was limited to files containing text. Text is crucial because it is how humans communicate with the computer. However, text files take up more space than needed to hold the information they do. Each character requires at least one byte. The number 3.1415926535 thus takes up 12 bytes, but if it is stored as a floating point number, it needs only 4 or 8, depending on the precision.

The file system on most computers also permits a variety of operations that have not been discussed. This includes reading from any point in a file, appending data to files, and modifying data. The need for processing data effectively is a main reason for computers to exist at all, so it is important to know as much as possible about how to program a computer for these purposes.

8.4.1 Binary Files

A *binary* file is one that does not contain text, but instead holds the raw, internal representation of its data. Of course, all files on a computer disk are binary in a sense, because they all contain numbers in binary form, but a binary file in this discussion does not contain information that can be read by a human. Binary files can be more efficient that other kinds, both in file size (smaller) and the time it takes to read and write them (less). Many standard files types, such as MP3, exist as binary files, so it is important to understand how to manipulate them.

Example: Create a File of Integers

The *array* type holds data in a form that is more natural for most computers than a list, and also has the **tofile()** method built in. If a collection of integers is written as a binary file, the first step is to place them into an array. If a set of 10,000 consecutive integers are to be written to a file named “ints,” the first step is to import the array class and open the output file. Notice that the file is open in “wb” mode, which means “write binary:”

```
from array import array
output_file = open('ints', 'wb')
```

Now create an array to hold the elements and fill the array with the consecutive integers:

```
arr = array('i')
for k in range (10000, 20000):
    arr.append(k)
```

Finally, write the data in the array to the file:

```
arr.tofile(out)
out.close()
```

This file has a size of 40 kb on a PC. A file with the same integers written as text is 49 kb. This is not exactly a large space savings, but it does add up.

Reading these values back is simple:

```
inf = open ('ints', 'rb')
arrin = array('i')
for k in range (0, 10001):
    try:
        arrin.fromfile(inf, 1)
    except:
        break
    print (arrin[k])
inf.close()
```

The **try** is used to catch an end of file error in cases where the number of items on the file is not known in advance.

Sometimes a binary file contains data that is all of the same type, but that situation is not very common. It is more likely that the file has strings, integers, and floats intermixed. Imagine a file of data for bank accounts or magazine subscriptions; the information includes names and addresses, dates, financial values, and optional data, depending on the situation (some customers have multiple accounts). By using *structs*, we can create binary files that contain more than one kind of information.

8.4.2 The Struct Module

The *struct* module permits variables and objects of various types to be converted into what amounts to a sequence of bytes. It is a common claim that this is in order to convert between Python forms and C forms, because C has a *struct* type (short for *structure*). However, many files exist that consist of mixed-type data in raw (i.e., machine compatible) form that have been created by many programs in many languages. It is possible that C is singled out because the name *struct* was used.

Example: A Video Game High Score File

Video game players need little incentive to try hard to win a game, but for many years, a special reward used to be given to the better players. The game "remembered" the best players and listed them at the beginning and end of the game. This kind of ego boost is a part of the reward system of the game. The game program stores the information on a file in descending order of score. The data that was saved was usually the player's name or initials, the score, and the date. This mixes string with numeric data.

Consider that the player's name is held in a variable **name**, the score is an integer **score**, and the date is a set of three strings **year**, **month**, and **day**. In this situation, the size of each value needs to be fixed, so allow 32 characters for the name, 4 for year, 2 for month, and 2 for day. The file was created with the name first, then the score, then the year, month, and day. The order matters because it will be read in the same order that it was written. In the file, the data appears as follows:

```
cccccccccccccccccccccccccccccccc iiii  cccc   cc    cc
Player's name                    Score Year  Month  Day
```

Each letter in the first string represents a byte in the data for this entry. "C" represents characters; "i" represents bytes that are part of an integer. There are 44 bytes in all, which is the size of one data *record*, which is what one set of related data is generally called. A file contains the records for all of the elements in the data set, and in this case, a record is the data for one player, or at least one time that the player played the game. There can be multiple entries for a player.

One way to convert mixed data like this into a *struct* is to use the **pack()** method. It takes a format parameter first, which indicates what the *struct* will consist of in terms of bytes. Then the values are passed that will be converted into components of the final struct. For the example here, the call to **pack()** is as follows:

```
s = pack ("32si4s2s2s", name, score, year, month, day)
```

The format string is 32si4s2s2s; there are 5 parts to this, one for each of the values to be packed:

32s is a 32-character long string. It should be of type *bytes*.

i is one integer. However, **2i** would be two integers, and **12i** is 12 integers.

4s is a 4-character long string.

2s is a 2-character long string.

Other important format items are as follows:

c is a character

f is a float

d is a double precision float

The value returned from **pack()** has the type *bytes*, and in this case, it is 44 bytes long. The high score file consists of many of these records, all of which are the same size. A record can be written to a file using **write()**. A program that writes just one such record is as follows:

```
from struct import *

f = open ("hiscores", "wb")
name = bytes("Jim Parker", 'UTF-8')
score = 109800
year = b"2015"
month = b"12"
day = b"26"
s = pack ("32si4s2s2s", name, score, year, month, day)
f.write(s)
```

Reading this file involves first reading the string of bytes that represents a data record. Then it is *unpacked*, which is the reverse of what **pack()** does, and the variables are passed to the **unpack()** function to be filled with data. The **unpack()** method takes a format string as the first parameter, the same kind of format string as **pack()** uses. It returns a tuple. An example that reads the record in the above code is as follows:

```
from struct import *

f = open("hiscores", "rb")
s = f.read(44)
name,score,year,month,day = unpack("32si4s2s2s", s)
name = name.decode("UTF-8")
```

```
year = year.decode("UTF-8")
month = month.decode("UTF-8")
day = day.decode("UTF-8")
```

The data returned by unpack are *bytes*, and need to be converted into strings before being used in most cases. Note the input mode on the **open()** call is "rb," or "read binary."

A file in this format has been provided, named "hiscore." When a player plays the game, they will enter their name; the computer knows their score and the date. A new entry must be made in the "hiscore" file with this new score in it. How is that done?

Start with the new player data for *Karl Holter*, with a score of 100,000. To update the file, it is opened and records are read and written to a new temporary file (named "tmp") until one is found that has a smaller score than the 100,000 that Karl achieved. Then Karl's record is written to the temporary file, and the remainder of "hiscores" is copied there. This creates a new file named "tmp" that has Karl's data added to it in the correct place. Now that file can be copied to "hiscores" replacing the old file, or the file named "tmp" can be renamed as "hiscores." This is called a *sequential file update*.

Renaming the file requires access to some of the operating system functions in the module *os*, in particular,

```
os.rename ("tmp", "hiscores")
```

8.4.3 Random Access

It seems natural to begin reading a file from the beginning, but that is not always necessary. If the data that is desired is located at a known place in the file, then the location being read from can be set to that point. This is a natural consequence of the fact that disk devices can be positioned at any location at any time. Why not files too?

The function that positions the file at a specific byte location is **seek()**:

```
f.seek(44)    # Position the file at byte 44,
              # which is the second record in the
              # hiscores file.
```

It's also possible to position the file relative to the current location:

```
f.seek(44, 1)    # Position the file 44 bytes from
                 # this location,
                 # which skips over the next
                 # record in hiscores.
```

A file can be re-wound so that it can be read over again by calling **f.seek(0)**, and it positions the file at the beginning. It is otherwise difficult to make use of this feature, unless the records on the file are of a fixed size, as they are in the file "hiscores," or the information on record sizes is saved in the file. Some files are intended from the outset to be used as random access files. Those files have an index that allows specific records to be read on demand. This is very much like a *dictionary*, but on a file. Assuming that the score for player *Arlen Franks* is needed, the name is searched for in the index. The result is the byte offset for Arlen's high score entry in the file.

Arlen's record starts at byte 352 (8th record multiplied by 44 bytes). He just played the game again and improved his score. Why not update his record on the file? The file needs to be open for input *and* output, so we use mode "rb+," meaning open a binary file for input and output. Then we position the file to Arlen's record, create a new record, and write that one record. This is a new approach, being able to both read and write the same file. However, if the data being written is exactly the same size as the record on the file, then no harm should come from it. The program is as follows:

```
# read and print hiscore file
from struct import *

f = open ("hiscores", "r+b") # Open binary file,input
                             # and output
pos = 44*8                   # Desired record is 8,
                             # 44 bytes per
f.seek(pos)                  # Seek to that position
                             # one the file
s = f.read(44)               # Read the target record
name = b'Arlen Franks'       # Make a new one with a
                             # new score
score = 100300
year = b'2015'
month = b'12'
```

```
day = b'26'                    # Pack the new data
ss = pack("32si4s2s2s", name,score, year,month,day)
f.seek (44*8)                  # Seek the original
                               # position again!
f.write(ss)                    # Write the new data over
                               # the old
f.close ()                     # Close the file
```

This works fine, provided that the position of Arlen's data in the file is known. It does not maintain the file in descending order, though.

Example: Maintaining the High Score File in Order

The circumstances of the new problem are that a player only appears in the high score file once and the file is maintained in descending order of score. If a player improves their score, then their entry should move closer to the beginning of the file. This is a more difficult problem than before, but one that is still practical. Let's presume that a player has achieved a new score. The entire process should be as follows:

Get the player's old score.	Read the file, get the player's record, unpack it.
Is the new score larger?	If not, close the file. Done.
Yes, so find out where the score belongs, in the file.	Look at successively preceding records until one is found that has a larger score.
Place the new record where it belongs.	Copy the records from the new position for the record ahead one position until the old position is reached.

The process is like moving a playing card closer to the top of the deck while leaving the other cards in the same order. It's probably more efficient to move the record while searching for the correct position, though. Each time the previous record is examined, if it does not have a larger score then the record being placed is copied ahead one position. This results in a pretty compact program, given the nature of the problem, but it is a bit tricky to get right. For example, what if the new score is the highest? What if the current high score gets a higher score? (see Exercise 11)

8.5 STANDARD FILE TYPES

Everyone's computer has files on it that the owner did not create. Some have been downloaded; some merely came with the machine. It is common practice to associate specific kinds of files, as indicated initially by some letters at the end of the file name, with certain applications. A file that ends in ".doc," for example, is usually a file created by Microsoft Word, and a file ending in ".mp3" is usually a sound file, often music. Such files have a format that is understood by existing software packages, and some of them (.gif) have been around for thirty years.

Each file type has been designed to make certain operations easy, and to pass certain information to the application. A set of de facto standards have evolved for how these files are laid out, and for what data are provided for what kinds of files.

8.5.1 Image Files

Images have been processed using computers since the 1960s, when NASA started processing images at the Jet Propulsion Laboratory. Scientists decided that having standards for computer images would be useful. The first formats were ad hoc, and based essentially on raw pixel data. Raw data means knowing what the image size is in advance, so headers were introduced providing at least that information, leading to the TARGA format (.tga) and tiff (Tagged Image File Format) in the mid-1980s. When the Internet and the World Wide Web became popular, the GIF was invented, which compressed the image data. This was followed by JPEG and other formats that could be used by Web designers and rendered by browsers, and each had a specific advantage. After all, reducing size meant reducing the time it took to download an image.

Many of the image file formats created in the 1980s are still being used. Some formats, like PNG (Portable Network Graphics), have been specifically designed for the Internet. Older ones (like JPEG) have found common uses in new technologies, like digital cameras.

8.5.2 GIF

The Graphics Interchange Format (GIF) is interesting. First, it uses compression to reduce the size of the file, but the compression method is not *lossy*, meaning that the image does not change after being compressed and then decompressed. The compression algorithm used is called LZW, which is discussed in Chapter 10. GIF uses a *color map* representation, so an element in the image is not a color, but instead is an index into an array that holds the color. That is, if **v = image[row][column]** then the color of that pixel is **(red[v], green[v], blue[v])**. The color itself could be a full 24 bits, but the value **v** is a byte, and so in a GIF there can only be 256 distinct colors. GIF uses a *little-endian* representation, meaning that the least significant byte of multi-byte objects comes first on the file.

One advantage of the GIF is that one of the colors can be made transparent. This means that when this color is drawn over another, the color below shows through. It is essentially a "do not draw this pixel" value. It is important for things like sprites in computer games. Another advantage of GIF is that multiple images can be stored in a single file, allowing an animation to be saved in a single file. GIF animations have been common on the Internet for many years, and while they usually represent small, brief animations such as Christmas trees with flashing lights, they can be as long and complex as television programs. Still, the fact that there can only be 256 different colors can be a problem.

A GIF is a binary file, but the first six characters are a header block containing what is called a *magic number*, or an identifying label. For a GIF file the three characters are always "GIF" and the next three represent the version; for the 1989 standard the first six characters are "GIF89a." Magic numbers are common in binary files, and are used to identify the file type. The file name suffix does not always tell the truth.

Following the header is the logical screen descriptor, which explains how much screen space the image requires. This is seven bytes:

Canvas width	2 bytes
Canvas height	2 bytes
Packed byte	1 byte

A set of flags and small values

Bit	8	7 6 5	4	3 2 1
	Global Color Table?	color resolution	sort flag	size of global color table

Background color index 1 byte

Pixel aspect ratio 1 byte

This is followed by the global color table, other descriptors, and the image data. The details can be found in manuals and online. The information in the first few bytes is critical, though, and the knowledge that LZW compression is used means that the pixels are not immediately available. Decompression is done to the image as a whole.

```
from struct import *
f = open ("test.gif", "rb")
s = f.read (13)               # Read the header
id,  ht, wd, flags, bci,par = unpack('6shhBBB', s)
#6s  h   h     B     B   B
f.close()
id = id.decode("utf-8")
print (id)
print ("Height", ht, "Width", wd)
print("Flags:", flags)
print ("Background color index: ", bci)
print ("Pixel aspect ratio:", par)
```

8.5.3 JPEG

A JPEG image uses a lossy compression scheme, and so the image is not the same after compression as it was before compression. For this reason, it should never be used for scientific or forensic purposes when measurements will be made using the image. It should never be used for astronomy, for example, although it is perfectly fine for portraits and landscape photographs.

The name JPEG is an acronym for the Joint Photographic Experts Group, and this refers to the nature of the compression algorithm. The file format is an envelope that contains the image, and it is referred to as JFIF (JPEG File Interchange

Format). The file header contains 20 bytes. The first 4 bytes are hex FF, D8, FF, and E0. Bytes 6–10 are "JFIF\0," and this is followed by a revision number. A short program that decodes the header is as follows:

```
from struct import *

f = open ("test.jpg", "rb")
s = f.read (20)                # Read the header
b1, b2,a1,a2,sz,id,v1, v2,unit,xd,yd, xt,yt =
unpack('BBBBh5sBBBhhBB', s)
#B  B   B  B  h 5s  B   B   B   h  h  B  B
f.close()
id = id.decode("utf-8")
print (id, "revision", v1, v2)
if b1==0xff and b2==0xd8:
    print ("SOI checks.")
else:
    print ("SOI fails.")
if a1==0xff and a2==0xe0:
    print ("Application marker checks.")
else:
    print("Application marker fails.")
print ("App 0 segment is", sz, "bytes long.")
if unit == 0:
    print ("No units given.")
elif unit == 1:
    print ("Units are dots per inch.")
elif unit == 2:
    print ("Units are dots per centimeter.")
if unit==0:
    print ("Aspect ratio is ", xd, ":", yd)
else:
    print ("Xdensity: ", xd, " Ydensity: ", yd)
if xt==0 and yt==0:
    print ("No thumbnail")
else:
    print ("Thumbnail image is ", xt, "x", yt)
```

The compression scheme used in JPEG is very involved, but it does cause certain identifiable artifacts in an image. In particular, pixels near edges and boundaries are smeared, essentially averaging the values across small regions (Figure 8.1). This can cause problems if a JPEG image is to be edited in Photoshop or Paint.

Figure 8.1
JPEG images tend to show artifacts at places where pixels change rapidly, like corners and edges.

8.5.4 TIFF

The *Tagged Image File Format* has a potentially large amount of metadata associated with it, and that is all in text form in the file. The device used to capture the image, the focal length of the lens, time, subject, and scores of other information can accompany the image. In fact, the TIFF has been seconded for use with numeric non-image data, as well. The other reason it is popular is that is can be used with uncompressed (raw) data.

The word *Tagged* comes from the fact that information is stored in the file using tags, such as might be found in an HTML file—except that the tags in a TIFF are not in text form. A tag has four components: an ID (2 bytes, what tag is this?), a data type (2 bytes, what type are the items in this tag?), a data count (4 bytes, how many items?), and a byte offset (4 bytes, where are these items?). Tags are identified by number, and each tag has a specific meaning. Tag 257 means *Image Height* and 256 is *Image Width*; 315 is the code meaning *Artist*, 306 means *Date/Time*, and 270 is the *Image Description*. They can be in any order. In fact, the whole file structure is flexible because all components are referenced using a byte offset into the file.

A TIFF begins with an 8-byte Image File Header (IFH):

Byte order: This is 2 bytes, and is "II" if data is in little-endian form and "MM" if it is big-endian.
Version Number: Always 42.
First Image File Directory offset: 4 bytes, the offset in the file of the first image.

The other important part of a TIFF is the Image File Directory (IFD), which contains information about the specific image, including the descriptive tags and data. The IFH is always 8 bytes long and is at the beginning of the file. An IFD can be almost any size and can be anywhere in the file; there can be more than one, as well. The first IFD is found by positioning the file to the offset found in the IFH. Subsequent ones are indicated in the IFD. The IFD stricture is as follows:

Number of tags: 2 bytes

Tags: Array of tags, size unknown

Next IFD offset: 4 bytes. File offset of the next IFD. If there are no more, then =0.

The structure of a tag was given previously, so a TIF is now defined. The image data can be, and frequently is, raw pixels, but can also be compressed in many ways as defined by the tags.

The program below reads the IFH and the first IFD, dumping the information to the screen:

```
# TIFF
from struct import *

f = open ("test.tif", "rb")
s = f.read (8)                          # Read the IFH
id,  ver, off = unpack('2shL', s)
#2s   h    L

id = id.decode("utf-8")
print ("TIFF ID is ", id, end="")
if id == "II":
    print ("which means little-endian.")
elif id == "mm":
    print ("which means big-endian")
else:
    print ("which means this is not a TIFF.")
print ("Version", ver)
print("Offset", off)

f.seek(off)                           # Get the first IFD
n = 0
b = f.read (2)                        # Number of tags
```

```
n = b[0] + b[1]*256
#n = int(s.decode("utf-8"))
for i in range(0,n):
    s = f.read (12)              # Read a tag
   id,dt,dc,do = unpack ("hhLL", s)
   print ("Tag ", id, "type", dt, "count", dc, "Offset", do)
f.close()
```

When this program executes using "test.tif" as the input file, the first two tags in the IFD are 256 and 257 (*width* and *height*), which are correct.

8.5.5 PNG

A PNG (Portable Network Graphics) file consists of a *signature* and consists of 8 bytes, and a collection of *chunks*, which resemble TIFF tags. There are 18 different kinds of chunk, the first of which is an image header. The signature is always 137 80 78 71 13 10 26 10. The bytes 80 78 71 are the letters "PNG."

A chunk has either 3 or 4 fields: a length field, a chunk type, an optional chunk data field, and a check code based on all previous bytes in the chunk that is used to detect errors (called a *cyclic redundancy check*, or CRC).

The image header chink (IHDR) has the following structure:

Image width:	4 bytes
Image height:	4 bytes
Bit depth:	1 byte. Number of bits per sample (1,2,4,8, or 16).
Color type:	1 byte. 0 (grey), 2 (RGB), 3 (color map), 4 (greyscale with transparency) or 6 (RGB with transparency)
Compression method:	1 byte. Always 0.
Filter method:	1 byte. Always 0.
Interlace method:	1 byte. 0=no interlace. 1=Adam7 interlace (see the references)

This file has compression, but it is non-lossy. It also, like GIF, allows transparency, but also allows full RGB color. It does not have an option for animations, though. Reading the signature and the first (IHDR) chunk is done in the following way:

```
# PNG
from struct import *
b2 = (137, 80, 78, 71, 13, 10, 26, 10) # Correct header
types = ("Grey", "", "RGB", "Color map",
         "Grey with alpha", "", "RGBA") # Color types
f = open ("test.png", "rb")
s = f.read (8)                # Read the header
b1 = unpack('8B', s)
if b1 == b2:
    print ("Header OK")
else:
    print ("Bad header")

s = f.read(8)  # The next chunk must be the IHDR
length, type = unpack (">I4s", s)  # Unpack the first 8 bytes
print ("First chunk: Length is", length, "Type:", type)

s = f.read (length)  # We know the length, read the chunk
wd,ht,dep,ctype,compress, filter, interlace = unpack(">ii5B",
s)
#I   I   B   B       B        B      B
print ("PNG Image width=", wd, "Height=", ht)
print ("Image has ", dep, "bytes per sample.")
print ("Color type is ", types[ctype])
if compress == 0:
    print ("Compression OK")
else:
    print ("Compression should be 0 but is", compress)
if filter==0:
    print ("Filter is OK")
else:
    print ("Filter should be 0 but is", filter)
if interlace==0:
    print ("No interlace")
elif interlace == 1:
    print ("Adam7 interlace")
else:
    print ("Bad interlace specified: ", interlace)
f.close()
```

8.5.6 Sound Files

A sound file can be more complex than an image file and substantially larger. To properly play back a sound, it is critical to know how it was sampled: how many bits per sample, how many channels, how many samples per second, compression schemes, and so on. The file must be readable in real time or the sound cannot be played without a separate decoding step. All that is really needed to display an image is its size pixel format and compression.

There are, once again, many existing audio file formats. MP3 is quite complex, too much so to discuss here. The usual option on a PC would be ".wav" and, as it happens, that format is not especially complicated.

8.5.7 WAV

A WAV file has three parts: the initial header, used to identify the file type; the format sub-chunk, which specifies the parameters of the sound file; and the data sub-chunk, which holds the sound data.

The initial header should contain the string "RIFF" followed by the size of the file minus 8 bytes (i.e., the size from this point forward), and the string "WAVE." This is 12 bytes in size.

The next sub-chunk has the following form:

ID:	= "fmt"
Size1:	Size of the rest of the sub-chunk
Format:	1 if PCM, another number if compressed
No. of Channels:	mono=1, stereo=2, etc.
Sample rate:	Sound samples per second. CD rate is 44100
Alignment:	Should be the number of channels multiplied by the sample rate multiplied by bits per sample divided by 8
Bits per sample:	AKA *quantization*. Bits in each sample: 8 and 12 are usual.

The final section contains the following:

ID:	= "data"
Size:	Number of bytes in the data
Data:	The actual sound data, as a large block of **Size** bytes.

A program that reads the first two sub-chunks is as follows:

```
# WAV
from struct import *

f = open("test.wav", "rb")
s = f.read (12)
riff,sz,fmt = unpack ("4si4s", s)
riff = riff.decode("utf-8")
fmt = fmt.decode("utf-8")
print (riff, sz, "bytes ", fmt)

s = f.read (24)
id, sz1, fmt,nchan,rate,bytes,algn, bps = unpack
    ("4sihhiihh", s)
#4s  i    h    h    i    i     h    h
id = id.decode ("utf-8)")
print ("ID is", id, "Channels ", nchan,
       "Sample rate is ", rate)
print ("Bits per sample is ", bps)
if fmt==1:
    print ("File is PCM")
else:
    print ("File is compressed ", fmt)
print ("Byterate was ", bytes, "should be ", rate*nchan*bps/8)
```

8.5.8 Other Files

Every type of file has a specific purpose and a format that is appropriate for that purpose. For that reason, the nature of the headers and the file contents differ. When a program is asked to open a file, there should be some way to confirm that the contents of the file can be read by the program. The code that has been presented so far is only sufficient to determine the file type and some of its basic parameters. The code needed to read and display a GIF, for example, would likely be over 1,000 lines long. It is important to see how to construct a file so that it can be used effectively by others and so that other programmers can create code that can identify that file and use it.

8.5.9 HTML

An HTML (HyperText Markup Language) file is one that is recognized by a browser and can be displayed as a Web page. It is a text file, and can be edited, saved, and redisplayed using simple tools.

The first line of text in an HTML file should be either

```
<!DOCTYPE html>
```

or

```
<html>
```

The problem is that these are text files, so spaces and tabs and newlines can appear without affecting the meaning. Browsers are also supposed to be somewhat forgiving about errors, displaying the page if at all possible. A simple example that shows some of the problems while being largely correct is as follows:

```
import webbrowser
f = open ("other.html")
html = False
while True:                  # Look at many lines
    s = f.readline()         # Read
    s = s.strip()            # Remove white space
                             #(blanks, tabs)
    s = s.lower()            # Convert to lower
                             # case for compare
    k = (s.find("doctype"))  # doctype found?
    if k>0:                  # Yes
        kk = s.find("html")  # Look also for 'html'
        if kk >= k+7:        # Found it, after DOCTYPE
            html = True      # Close enough
            break
    else:
        k = s.find("html")          # No 'doctype'. 'html'?
        if k>0 and s[k-1] == "<":   # Yes. Preceded by '<'?
            html = True             # Yes, Close enough.
            break
    if len(s) > 0:           # is the string non-blank?
        html = False         # Yes. So it is not
                             # HTML probably
        break
```

```
if html:
    webbrowser.open_new_tab('other.html')
else:
    print ("This is not an HTML file.")
```

This program uses the *webbrowser* module of Python to display the web page if it is one. The call `webbrowser.open _ new _ tab('other.html')` opens the page in a new tab, if the browser is open. This module is not a browser itself. It simply opens an existing installed browser to do the work of displaying the page.

8.5.10 EXE

This is a Microsoft executable file. The details of the format are challenging to understand, and require a knowledge of computers and formats beyond a first-year level, but detecting one is relatively simple. The first two bytes that identify an EXE file are as follows:

Byte 0: 0x4D

Byte 1: 0x5a

It is always possible that the first two bytes of a file will be these two by accident, but it is unlikely. If the file being examined is, in fact, an EXE file, then a Python program can execute it. This uses the operating system interface module *os*:

```
import os
os.system ("program.exe")
```

8.6 SUMMARY

Computer science is a discipline that concerns itself with information. Computers can only operate on numbers, so an important aspect of using data is the representation of complex things as numbers. Most data consist of measurements of something, and as such are fundamentally numeric.

A *dictionary* allows for a complex indexing scheme: it is accessed by content. A dictionary can be indexed by a string or tuple, which in general would be referred to as a *key*, and the information at that location in the dictionary is said to be *associated* with that key.

A Python *array* is a class that mimics the array type of other languages and offers efficiency in storage, exchanging that for flexibility. The *struct* module permits variables and objects of various types to be converted into what amounts to a sequence of bytes. It has the **pack()** and **unpack()** methods for converting Python variables into sequences of bytes.

The string **format()** method allows a programmer to specify how values should be placed within a string. The idea is to create a string that contains the formatted output, and then print the string.

Python data can be written to files in raw, binary form. It is also possible to position the file at any byte in a binary file, allowing the file to be read or written at any location.

Exercises

1. Ask the user for a file name. Extract the suffix and use it to look up the type of the file in a dictionary and print a short description of it. Recognized types include image files (jpg, gif, tiff, and png), sound files (wav), and others (dll and exe).
2. Modify the Latin translation program so that it asks the user for a translation of any word it cannot find and adds that word to the dictionary.
3. Write a program that reads keys and values (strings) from the console and creates a dictionary from those data. When the user types the word "done," then the input is complete. City names are good examples of values, and could represent the city where the person named in the key lives.
4. Modify the answer to Exercise 3 so that after the data entry is complete, the user can enter a value and the program will print all of the keys associated with that value.
5. Given a dictionary, write a function **writedict()** that writes that dictionary to a file, and another function **readdict()** that will read that file and recreate the dictionary. For simplicity, assume that the keys are simple numbers or strings.
6. The PNM file format for images has three types of image in two forms: monochrome, grey, and color, saved as text or in binary form. A binary grey level image is called a PGM (Pixel Grey Map) and has a short header

followed by pixels. The header is text and consists of the identifying code "P5" followed by the width of the image in pixels (NC), followed by the height (NR), followed by the maximum value for a grey level (NGL) followed by an end of line. Now the data follows as rows of NC bytes:

P5

nc nr ngl

<image pixels, 1 byte each>

Write a program that reads an image file in this format and displays it on the screen as an image.

http://netpbm.sourceforge.net/doc/pgm.html

7. Assume that the following variables exist and have the obvious meanings: year, month, day, hour, minute, and second. All are integers, except second, which is a float. The ISO 8601 standard for displaying dates uses the format

YYYY-MM-DDThh:mm:ss.s

where the letter "T" ends the date portion and begins the time. An example is as follows:

2015-12-27T10:38:12.3

Write a function that takes the given variables as parameters and prints the date in this format.

http://www.w3.org/TR/NOTE-datetime

8. Write a Python program that opens a file named by the user from the keyboard; the file has the suffix .jpg, .gif, or .png. Determine whether the file contents agree with the suffix, and print a message indicating the result.

9. A concordance is a list of words found in a text. Build a concordance using a dictionary that keeps track of the number of times that a word is used, in addition to its mere presence. Print the resulting list in alphabetical order.

10. Write a program that prints out checks. The date and the payee are entered as strings and the amount is entered as a floating point number, the maximum amount being $1,000. The FOR field is always "Books." The program formats the check according to the following image (Figure 8.2), where

The date is on line 3, starting at character 58.

The PAY TO field is on line 6, starting at character 20.

The numeric amount is on line 6, starting at character 57.

The text amount is on line 8, character 10.

The FOR field is on line 12, character 15.

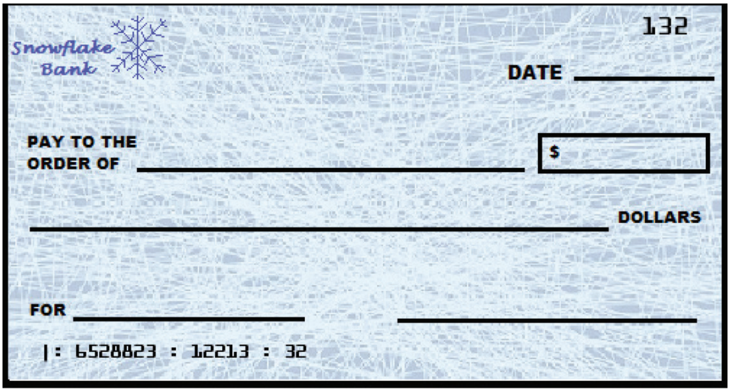


Figure 8.2
Check format.

Notes and Other Resources

List of free datasets to download: *https://r-dir.com/reference/datasets.html*

NASA Meteorite Landing Database: *https://data.nasa.gov/view/ak9y-cwf9*

String Formatting: *https://infohost.nmt.edu/tcc/help/pubs/python/web/format-spec.html*

The Array type: *https://docs.python.org/3/library/array.html*

Image file formats: *https://www.library.cornell.edu/preservation/tutorial/presentation/table7-1.html*

http://www.scantips.com/basics09.html

Home page for MPEG: *http://mpeg.chiariglione.org/*

GIF 1989 specification: *http://www.w3.org/Graphics/GIF/spec-gif89a.txt*

Byte by byte GIF: *http://www.matthewflickinger.com/lab/whatsinagif/bits_and_bytes.asp*

TIFF description: *http://www.fileformat.info/format/tiff/egff.htm#TIFF.FO*

PNG specification: *http://www.w3.org/TR/PNG/*

Adam7 interlacing: *http://www.libpng.org/pub/png/pngpics.html*

EXE file format: *http://www.delorie.com/djgpp/doc/exe/*

File signatures: *http://www.garykessler.net/library/file_sigs.html*

Sample PGM images: *http://people.sc.fsu.edu/~jburkardt/data/pgmb/pgmb.html*

1. Gunter Born. (1995). *The File Formats Handbook*, Cengage Learning EMEA, ISBN-13: 978-1850321170.
2. David Kay. (1994). *Graphics File Formats*, Windcrest, ISBN-13: 978-0070340251.
3. Dr. Charles R. Severance. (2013). *Python for Informatics: Exploring Information*, CreateSpace Independent Publishing Platform, ISBN-13: 978-1492339243.
4. Alan Tharp. (1988). *File Organization and Processing, 1st edition,* John Wiley & Sons, ISBN-13: 978-0471605218.
5. John Watkinson. (2001). *MPEG Handbook*, Focal Press, ISBN-13: 978-0240516561.

CHAPTER 9

MULTIMEDIA

In this chapter

For many people, computers have become the platform of choice for the delivery of entertainment, education, and information. Part of the reason for this is the ubiquity and speed of the Internet, but the main reason is that computers can deliver media in almost any form: text, images, sound, video, animation, and mixtures of all of these. If someone has something to say, the computer can present it to the world in full color and 5.1 channel sound. Moreover, the availability of free and inexpensive tools for content creation allows almost anyone to be a music producer or film director.

Python can be used to process and display most forms of media through packages that can be downloaded and installed. There are many of these and multiple versions in an array of combinations. It is not possible to discuss all of the ways that Python can be used to do multimedia, and all of the packages and libraries that help programmers implement these things. A tool has already been described for displaying images and graphics (*Pygame*). Why not simply add more media capability to it and build on what has already been discussed?

Many of the graphics aspects of Pygame were discussed in Chapter 7, and so the modules have probably been installed in your computer.

It is essential to install a version of *Pygame* that works with Python 3.

What is discussed in this chapter are extensions of simple computer graphics into a dynamic feature set that is called *digital media*. This includes using interface devices, such as the mouse and touch screens, displaying animations and videos, and playing sound.

9.1 MOUSE INTERACTIONS

Using mouse position and button presses is a basic form of communication with a computer. The use of the mouse position to activate some visual device on the screen like a button is familiar to everyone who uses a computer, although it is being gradually replaced by touch screens. When the user moves the mouse, a cursor or indicator moves correspondingly. The position of this cursor indicates a point on the screen that is active in some way, and if a graphical device is there, then it can be manipulated using the mouse buttons. The problem is that a mouse button press can occur at any time; it is unpredictable. This is what programmers call an *event*: something that happens at an unpredictable moment that must be dealt with. Some software someplace must be watching the mouse at all times, determining the x and y coordinates of the cursor on the screen and drawing the cursor in the correct place.

Pygame continually updates the position of the mouse, which means the location of the mouse cursor on the computer screen in x,y coordinates. which can be accessed using function **getpos**:

```
pygame.mouse.get_pos()
```

which returns a tuple (mx, my) with the mouse coordinates. This is perfectly fine, but can be a bit awkward. The x position of the mouse is **pygame.mouse.get_pos()[0]**, for example. It reads poorly. One suggestion would be to have functions **mouseX()** and **mouseY(),** which return the most recent x and y coordinates. It costs some execution time, but often looks better in the code.

```
def getX():
  return pygame.mouse.get_pos()[0]
```

```
def getY():
  return pygame.mouse.get_pos()[1]
```

Another suggestion is to place the following code at the beginning of the event loop:

```
mouseX, mouseY = pygame.mouse.get_pos()
```

This would mean that the variables mouseX and mouseY would always hold the current mouse position.

Example: Draw a Circle at the Mouse Cursor

Drawing a circle at the current mouse position involves repeatedly determining the mouse position and then drawing a circle at that set of coordinates. This should be done within a **draw()** function or the main loop. An example implementation is as follows:

```
import pygame

FPS = 30
screen = pygame.display.set_mode((400, 400))
clock = pygame.time.Clock()

while True:
    clock.tick(FPS)
    mouseX, mouseY = pygame.mouse.get_pos()
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
    screen.fill((200,200,200))
    pygame.draw.circle (screen, (200,0,0), (
                        mouseX, mouseY), 20, 2)
    pygame.display.update()
```

The result is a red circle that follows the mouse. The **screen.fill** function sets the background color to a grey level of 200. The circle call draws the circle 30 times per second, every time the event loop executes. The most recent mouse position is always found using the functions variables **mouseX** and **mouseY**, set at the top of the loop. It is necessary to call **screen.fill()** each time the loop executes because it erases the previous screen, drawing over it. If this were not done, then multiple circles would appear on the screen, one for each time the event loop executed (Figure 9.1).

Example: Change Background Color Using the Mouse

The idea here is to change the background color based on the mouse position. There are only two directions to move, horizontally or vertically, so one of the three colors remains constant; let that color be blue. The horizontal mouse position controls the red value, with the leftmost position representing no red and the rightmost representing full red (255). Similarly, the mouse at the bottom of the image represents no green, and at the top it represents full green. The background color will be changed during the event loop (using **screen.fill**).

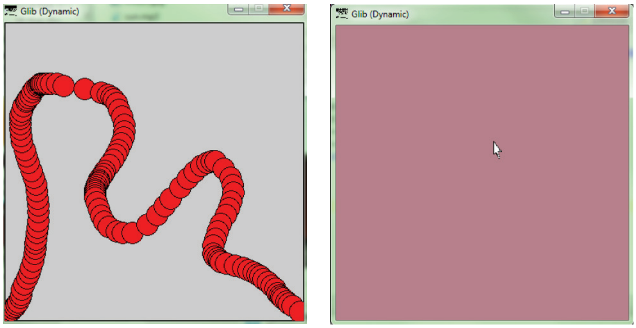


Figure 9.1
Using the mouse to control elements of a display.

Given that the position of the mouse on the screen is given by **mouseX**, the value of the red coordinate will be **(mouseX/width*255)**. It may require a change in x coordinate of multiple pixels to shift the color by one unit. A similar expression is used to change the green value.

The program is as follows:

```
import pygame
FPS = 30
width = 400
height = 400
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()

while True:
    clock.tick(FPS)
    mouseX, mouseY = pygame.mouse.get_pos()
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
```

```
r = (mouseX/width) *255.0
g = (mouseY/height)*255.0
screen.fill ((r, g, 128))
pygame.display.update()
```

From now on only the key parts of the program will be shown, and not the entire initialization and event loop.

9.1.1 Mouse Buttons

Mouse button *clicks*, as they are called, can be retrieved by writing a function that handles them. Each time a mouse button is pressed Pygame indicates an event that can be identified in the main event loop. Events can be ignored, of course.

All Pygame code so far contains the statements:

```
for event in pygame.event.get():
    if event.type == pygame.QUIT:
        quit()
```

The variable **event** is set by Pygame to some *thing* that happened. The pygame.QUIT event refers to the end of the program, perhaps by the user clicking the “X” in the upper right corner or some other way. Mouse actions are also events. A mouse button can be *pressed* or *released*, and when both happens, we call that a mouse *click*. The mouse button pressed event is an event type named pygame.MOUSEBUTTONDOWN and can be handled in the same way as the QUIT event is handled:

```
if event.type == pygame.MOUSEBUTTONDOWN:
         do something …
```

Similarly, when the mouse button is released, we can capture that event, too:

```
if event.type == pygame.MOUSEBUTTONUP:
         do something …
```

If we write a function named **mousePressed()** that is called within the event loop when the mouse button is depressed and a corresponding function **mouseReleased** for when the mouse button is released, than the event loop does not get cluttered with the details of what the specific mouse operation is doing, only that it has happened. The details are left to the two functions. If the mouse button is pressed, then the mouse is moved, and then it is released, the coordinates of the press and the release point will be different, and both can be retrieved. For example, when the mouse button is pressed, the mouse coordinates could be saved as the beginning of a line, and when released, the coordinates could be the end of the line. Multiple lines could be drawn in this way.

Example: Draw Lines Using the Mouse

Using the scheme described above, the function **mousePressed()** will store the mouse position in global variables **x0** and **y0**, and **mouseReleased()** will store the release coordinates at **x1** and **y1**. **mouseReleased()** will also draw the line from (x0,y0) to (x1, y1):

```
def mousePressed ():
    global x0, y0
    x0 = mouseX
    y0 = mouseY

def mouseReleased ():
    global x1, y1
    x1 = mouseX
    y1 = mouseY
    pygame.draw.line(screen, (0,0,0), (x0, y0), (x1,y1), 2)
```

Drawing is performed inside of **mouseReleased()**. Within the event loop, these functions are called when the mouse events occur:

```
for event in pygame.event.get():
     . . .
     if event.type == pygame.MOUSEBUTTONDOWN:
         mousePressed()
     if event.type == pygame.MOUSEBUTTONUP:
         mouseReleased()
```

A mouse usually has more than one button. We'll modify these functions later to accept a parameter, which will be an indicator of what button was pressed.

Example: A Button

This example program changes the background color of the drawing window when a graphical button is pressed. A button, in the user interface sense, is a rectangular region on the computer screen that responds to a mouse click with a specific action. It is a two-part process: when the mouse cursor enters the rectangular region, the button is said to be *activated*. Sometimes it will be caused to change color at this point, or some other action will be performed that indicates that it is ready to function. When a mouse button is pressed while the button is activated, then some action occurs, usually as defined by a function being called. The basic idea is simple enough to implement, although some buttons can have complex actions such as sounds, images, and irregular shapes.

The cursor is within a rectangular region when its coordinates are greater than the upper left coordinate of the rectangle and smaller than the lower right coordinates. When that occurs, the button is ready to be pressed, and should change color. This does not require anything but knowledge of the mouse coordinates. It the left button is pressed in this state (activated) then the action defined by the button will occur; the background color will change, in this case. The program begins as normal, with imports and initialization. Here is a program that does this for a button at (100, 100) that is 60x20 pixels in size:

```
def draw ():
    global bc, w, h, x0, x1, y0,
    y1, active
    screen.fill (bc)# Fill with
                    # color bc
    x = mouseX # Is the mouse
               # in the rect
    y = mouseY
    if x>x0 and x<x0+w and
      y>y0 and y<y0+h:    # Yes.
#  Button is active. Green
        c =  (50, 200, 50)
        active = True
    else:
        c = (200, 50, 50)
# NO. Button is inactive. Red
        active = False
    pygame.draw.rect(screen, c,
     (x0, y0, w, h))   # Draw the
                       # button

def mouseReleased ():
    global active, bc
    if active:
# Button active? Left button
# released?
# If so generate a random color.
      bc = (randrange(100, 200),
            randrange(100, 200),
            randrange(100, 200))
```

```
x0 = 100   # upper left button
           # position
y0 = 100
w = 60       # Button size
h = 20
bc = (200,200,200) # Initial
                   # color
active = False   # Is the
                 # button active?
while True:
    clock.tick(FPS)
    mouseX, mouseY =
       pygame.mouse.get_pos()
    for event in pygame.event.
                          get():
        if event.type == pygame.
                            QUIT:
             quit()
         if event.type ==
pygame.MOUSEBUTTONDOWN:
             mousePressed()
         if event.type ==
pygame.MOUSEBUTTONUP:
             mouseReleased()
    draw()
    pygame.display.update()
```

All of the software buttons everywhere work in basically this way.

9.2 THE KEYBOARD

Like the mouse motions and button presses, pressing a key on the keyboard is an *event*. Like button presses, a key press is a single event with multiple options. The fact that a key has been pressed is an event, and exactly which key it was is a detail, just as it was when a mouse button was pressed. It is important to understand that using a standard Python function such as **input()** will not be successful when trying to read from the keyboard with an event-driven system, although knowing about events can be valuable in understanding how **input()** could be implemented. When **input()** is called, it does not return until a line has been read; the keyboard events capture the key press when it occurs. It appears that a call to **input()** may involve many key press events. What software receives them? That is the important question. The situation is too confusing to be resolved sensibly, so the rule is: *never use **input()** and related functions when handling key presses*. It is acceptable to call **print()** because it is printing to a console device for which no conflict exists.

Every key press will eventually correspond to a key release, so there are again two events for handling them:

```
    if event.type == pygame.KEYDOWN:
#           A key was depressed.

    if event.type == pygame.KEYUP:
#           A key was released.
```

Which key was it? That's stored in the variable **event.key**, but not as a character proper, but as a code. The character "a" is coded as pygame.K_a, and "+" is **pygame.K_PLUS**. The left arrow key is **pygame.K_LEFT**. A list of all keys can be found at

https://www.pygame.org/docs/ref/key.html?highlight=keyboard

Code presented here often calls functions **keyPressed(k)** and **keyReleased(k)** when the keyboard events occur. The parameter **k** is the value of the key that was pressed or released.

keyPressed(k): called when a key is pressed. Parameter **k** is the key that was pressed.

keyReleased(k): called when a key is released. Parameter **k** is the key that was released.

In an event-driven program, it is unusual for key presses to be converted into strings, as they normally would be in a typical console-style program. That's because it is expected that the interface to the event-driven program will be through mouse *gestures* (movements) and using single key commands from the keyboard, like "up arrow" meaning "move forward."

Example: Pressing a "q" Creates a Random Circle

This program draws a circle at a random location when the "q" key is pressed. The old circles will remain. This illustrates the use of the keyboard in an obvious way. The initialization is to clear the screen and set the background color and fill color. The **keyPressed()** function generates random x,y coordinates and draws a circle there:

```
def keyPressed (k):
    if k.key == pygame.K_q:
        pygame.draw.circle(screen,  c,  (randrange(0,width),
                           randrange(0,height)),30, 3)
```

The key value is passed as an *event* rather than the key for a simple reason: Pygame does not decode all keys, but provides an indication of what keys have been pressed. What this means is that there is no uppercase "A;" instead, the system returns an event that tells us that the "a" key has been pressed and so has a SHIFT key. It is the programmer's job to determine what this means. That might seem odd, but remember that Pygame was developed for building games. Keys being pressed can mean quite different things within a game than they do in a word processing programs.

So, in the event loop, we do this:

```
if event.type == pygame.KEYDOWN:
    keyPressed(event)
```

Within the **keyPressed** function, we can decode this to mean what we wish. Let's draw a circle when the "+" key is pressed instead of "q." The "+" key is the "=" key AND a shift, so the function is as follows:

```
def keyPressed (k):
    if k.key == pygame.K_EQUALS and k.mod&pygame.KMOD_SHIFT:
        pygame.draw.circle(screen, c, (randrange(0,width),
                           randrange(0,height)),30, 3)
```

The keys that can modify the value of another key are referred to as *modifiers* and are available as a variable **event.mod**. More than one modifier can be applied at a time: a common example on a PC is CONTROL-ALT-DELETE. All modifiers need to be obtainable, so they are specified as specific bits within the **mod** variable, and bits for all of the applicable modifiers are set. That's why the expression **k.mod&pygame.KMOD_SHIFT** was used in the code above. It checks to see if the *shift* key was depressed, as indicated by the **KMOD_SHIFT** bit, at the same time as the "=" key was depressed. The result, in this case at least, is "+."

Example: Reading a Character String

There are some reasons why an event-driven program might wish to read data from the user as a string. Perhaps a name is required, or a key value to access a database, or a password. Whatever the reason, it should be possible to read a string using the keyboard events passed to **keyPressed()**. The way it would normally be done is to read one character at a time, and construct a string by concatenation. That's how this program works:

```
def keyPressed(k):
    global s, t
    if k.key == pygame.K_RETURN:
        t = s
        s = ""
        return
    if k.key == pygame.K_BACKSPACE and len(s)>0:
        s = s[:-1]
    else:
        s = s + chr(k.key)

def draw ():
    global s, t
    screen.fill((200,200,200))
    text ("Enter a string: ", 10, 100, 24, f)
    text (s, 20, 130, 24, f)
    print("    ", len(s), s)
    if (t != ""):
        text ("Completed string is "+t, 20, 150, 24, f)
```

The global variable **s** holds the string being built, and the string **t** holds the final string. Characters are captured from the keyboard by **keyPressed()** and fall into one of three categories:

1. Most characters are added to the global string **s** through concatenation. The character passed to **keyPressed()** is through the *event*. The **chr()** function converts it to a character, which is added to the end of **s**.
2. A BACKSPACE deletes the last character typed from the string. This is done using a substring from 0 to the second last character.
3. A RETURN ends the string. The current string in **s** is assigned to **t**, and **s** is reset to an empty string.

This kind of string data entry is especially useful when entering file names and numeric parameters. There are frequently special interface objects (*widgets*) that perform these tasks, such as *text boxes*. Pygame could be used to implement such a widget (see Exercise 6).

9.3 ANIMATION

Making graphical objects change position is simple, but making them seem to move is more difficult. Animation is something of an optical illusion; images are drawn in succession so quickly that the human eye cannot detect that they are distinct images. Small changes in position in a sequence of these images are seen as motion rather than as a set of still pictures. A typical animation draws a new image (*frame*) between 24 and 30 times per second to make the illusion work.

There are two kinds of animation that can be done using *Pygame*. The first involves objects that consist of primitives that are drawn by the library. A circle can represent a ball, for instance, of a set of rectangles and curves could be a car. The second kind of animation uses images, where each image is one frame in the sequence. These images are displayed entirely in rapid succession to create the animation. In the first case, the animation is being created as the program executes, whereas in the second, the animation is complete before the program runs, and the program really just puts it on the screen.

9.3.1 Object Animation

Animating an object involves updating its position, speed, and orientation at small time intervals, so all of these aspects of the object must be kept in variables. If there are many objects being animated, then all of these variables must exist for each object, and are updated at the end of each time interval. If the animation is displaying 30 frames per second then a new frame is drawn every 0.03

seconds. In Pygame, we control the frame rate using **clock.tick(FPS)**, which does not return until a duration of 1/FPS seconds has passed. We control the rate by changing the value of **FPS**.

Example: A Ball in a Box

Imagine a ball bouncing in a square box. A box has three dimensions, of course, but for this example, it is restricted to two, so it looks like a circle within a square. The ball is moving, and when it strikes one of the sides of the square, it bounces, thus changing direction. There is one moving object: the ball. Graphically, it is simply a circle, with position **x,y** and speed **dx** in the x direction and **dy** in the y direction. It will have size 30 pixels. The box is the window the circle is drawn in.

During each frame, the ball moves **dx** pixels in the x direction and **dy** pixels in the y direction, so within the **draw()** function the position is updated as

```
x = x + dx
y = y + dy
```

This new position is where to draw the circle. However, if the ball is outside of the box after it is moved, then a bounce has to be performed. That is, if the new position of x is, for instance, less than 0, then it would have struck the left side of the square and then changed to the x direction (bounced). In this case, and also if x>width, the bounce is implemented by

```
dx = -dx
```

Similarly, if the y coordinate of the ball becomes less than 0 or greater than the height, then it bounces vertically:

```
dy = -dy
```

This would all be true if the ball were very tiny, a single point, but it has a size of 30 pixels, and the coordinates of the circle are the coordinates of its center. This means that the method described above will bounce the circle only after the center coordinate passes the boundary, meaning that half of the circle is already on the other side. It's easy to fix: the ball is 30 pixels in size, so it should bounce when it gets within 15 pixels of any boundary. For example, the x bounce should occur when **x<=15 or x>=width-15**. The entire solution is as follows:

```
def draw ():
    global dx, dy, x, y
    screen.fill( (200, 200, 200) ) # Erase the prior frame
    x = x + dx                     # Change ball position
    y = y + dy
    if x<=15 or x>=width-15:       # Bounce in X direction?
        dx = -dx
    if y<=15 or y>=height-15:      # Bounce in Y direction?
        dy = -dy
    pygame.draw.circle(screen, fill, (x, y), 15)
                                              # Draw the ball

width = 300
height = 300
x = 100                       # Initial x position of the ball
y = 100                       # Initial y position
dx = 3                        # Speed in x
dy = 2                        # Speed in y
fill = (30, 200, 20)          # Fill with green
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 30
while True:
    clock.tick(FPS)
    mouseX, mouseY = pygame.mouse.get_pos()
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
    draw()
    pygame.display.update()
```

Eight frames from this animation showing the ball bouncing in a corner of the box are shown in Figure 9.2. An entire second's worth of frames (30) are given on the accompanying disk.

If there are many objects, then all of the positions and speeds, and perhaps even shape, size, and color would have to be kept and updated during each frame. There are two usual ways to do this. In the first case, the parameters are kept in arrays (lists). There would be an array of x coordinates, an array of y coordinates, of speeds, and so on. Each frame could involve an update to all elements of the arrays. Updating the position can be done using the following code:

```
for i in range(0,Nobjects):
    x[i] = x[i] + dx[i]
    y[i] = y[i] + dy[i]
```

The other usual method for handling multiple objects is to create an object *class* that contains all of the parameters needed to display the object. There is still an array, but it is an array of object instances, and if it is cleverly programmed the class can be updated by calling an **update()** method:

```
for i in range(0,Nobjects):
    ball[i].update()
```

Example: Many Balls in a Box

This example uses the same premise as the previous one, but will draw many balls in the window, all of them bouncing. Both methods for keeping track of objects, arrays, and classes, are illustrated. The *many arrays* solution has lists for x and y, for dx and dy, for color and for size. All parameters are initialized at random when the program begins.

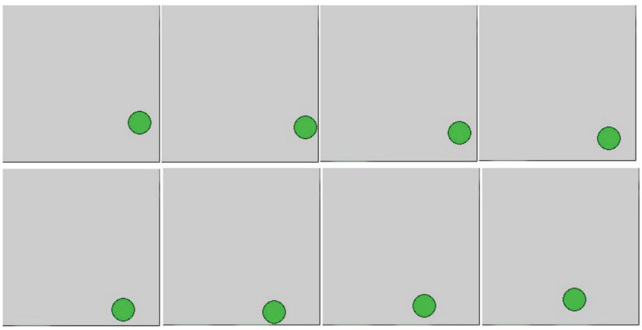


Figure 9.2
Bouncing ball in a box

The solution that uses classes defines a class **ball** within which the position, speed, color, and size are defined. The constructor initializes the values and the update method changes the ball's position and performs any needed bounces. The two solutions are as follows:

Arrays	Class

`# Bouncing ball animation.`
`import pygame`
`from random import *`
`def draw ():`
`    global dx, dy, x, y`
	`import pygame`
	`from random import *`
	`class Ball:`
	`    def __init__ (self, width,`
	`                  height):`

```
    screen.fill( (200, 200, 200) )
                 # Erase the prior frame
    for i in range(0,n):
        x[i] = x[i] + dx[i]
                       # Change position
        y[i] = y[i] + dy[i]
        if x[i]<=sizes[i]/2 or
x[i]>=width-sizes[i]/2: # Bounce X?
            dx[i] = -dx[i]
        if y[i]<=sizes[i]/2 or
y[i]>=height-sizes[i]/2:# Bounce Y?
            dy[i] = -dy[i]
        pygame.draw.circle(screen,
        colors[i], (x[i], y[i]),
        int(sizes[i]/2))

n = 50
x = [] # Initial x position of the
       # balls
y = [] # Initial y position
dx = []# Speed in x
dy = [] # Speed in y
colors = []
sizes = []
width = 400
height = 400
for i in range (0,n):
    x = x + [randrange(15,width-15)]
    y = y + [randrange(15,height-15)]
    dx = dx + [randrange (-2, 2)]
    dy = dy + [randrange (-2, 2)]
    sizes = sizes + [randrange
                       (2,30)]
    colors = colors +
              [(randrange(100, 200),
                randrange(100, 200),
              randrange(100, 200)),]

screen = pygame.display.
           set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 30
while True:
    clock.tick(FPS)
    mouseX, mouseY = pygame.mouse.
                         get_pos()
    for event in pygame.event.get():
        if event.type == pygame.
```

```
        self.x = randrange
(15, width-15)
        self.y = randrange
(15, height-15)
        self.dx = randrange (-2, 2)
        self.dy = randrange (-2, 2)
        self.size = randrange (2, 30)
        self.color = (randrange
                           (100, 200),
      randrange (100, 200),randrange
    (100, 200),randrange (100, 200))

    def draw (self):
        self.x = self.x + self.dx
                       # Change position
        self.y = self.y + self.dy
          if self.x<=self.size/2 or
self.x>=width-self.size/2:
                             # Bounce X?
            self.dx = -self.dx
          if self.y<=self.size/2 or
self.y>=height-self.size/2:
                             # Bounce Y?
            self.dy = -self.dy
        fill = (self.color[0],
                    self.color[1],
                    self.color[2],
                    self.color[3])
        pygame.draw.circle(screen,
            fill, (self.x, self.y),
                 int(self.size/ 2))
                       # Draw the ball

def draw ():
    global dx, dy, x, y
    screen.fill((200, 200, 200))
# Erase the prior frame
    for i in range(0,n):
        balls[i].draw()

width = 400
height = 400
n = 50
balls = []
for i in range (0,n):
    balls = balls + [Ball(width,
                          height)]
screen = pygame.display.set_
              mode((width, height))
```

```
QUIT:
            quit()
    draw()
    pygame.display.update()
```

```
clock = pygame.time.Clock()
pygame.init()
FPS = 30
while True:
    clock.tick(FPS)
    mouseX, mouseY =
             pygame.mouse.get_pos()
    for event in pygame.event.get():
       if event.type == pygame.QUIT:
            quit()
    draw()
    pygame.display.update()
```

These two solutions illustrate how classes work very neatly. The class contains individual properties of a ball and many are created; the arrays contain many instances of each property. So **x[i]** and **ball[i].x** represent the same thing. In this case, the two programs are about the same size, but the class-based implementation encapsulates the details of the ball and what can be done with it. The class-based **draw()** function only says “draw each ball,” but in the array implementation, the **draw()** function looks at all of the details of all balls to draw them. One of the implications is that it would be possible to divide the labor between two persons, one who wrote the class and another who wrote the rest of the code.

9.3.2 Frame Animation

The hard work in frame animation is done before the computer program is written. An animator has created drawings of an object in various stages of movement. All the program does is display frames one after the other, often looping them to create the desired effect. A common example of this is the animation of *gait*, walking or running. An artist draws multiple stages of a single step, being careful to ensure that timing is correct: how long does it take for a normal person to stake a pair of steps (left, right)? This time should agree with the frames the artist creates. If it takes one second to make the step, then it should be drawn as 30 frames.

Other kinds of animation are performed, too. A fire can be animated as a very few frames, as can smoke and water. The program that draws the animation reads all of the image files into a collection. When the animation is played, the program displays one image after another within the draw function. This can be complicated by the fact that there may be multiple animations playing at the same time, possibly of different lengths and frame sizes.

Example: Read Frames and Play Them Back as an Animation.

In this example, there are 10 drawn animation frames of a cartoon character walking. These frames are intended to represent a single gait cycle, and so should be repeated. The program does the following: when the "up arrow" key is pressed and held down, the character drawn in the window "walks;" otherwise, a still image is displayed.

First, the images should be read in and stored in a *list* so that they can be played repeatedly. Then the **draw** function should be written so that when called it displays the next frame, which is one of the images in the list, and increments the frame count. A list named **frames** is initialized with all of the images in the sequence.

```
def draw ():
    global f
    screen.blit (frames[f], (0, 0))
    f = f + 1
    if (f > 10):
        f = 1
```

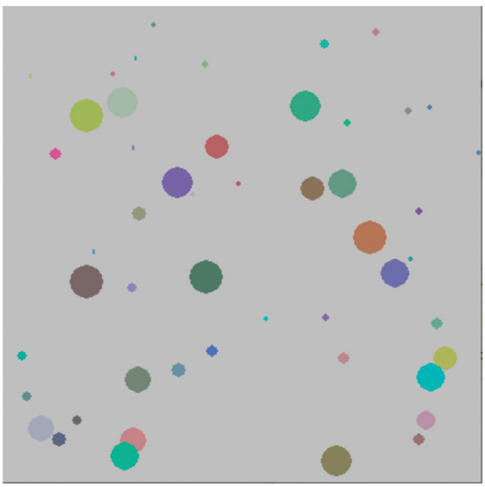


Figure 9.3
Many bouncing balls in a box.

It cycles through the frames and repeats when all have been displayed.

The initialization can be a simple matter of reading ten images into variables and creating a list. This code does it in a loop, using a number in the name and incrementing it:

```
frames = []
for i in range (1, 10):
    s = "images/a00"+str(i) +".bmp"
    x = pygame.image.load (s)
    frames = frames + [x,]
x = pygame.image.load ("images/a010.bmp")
frames = frames + [x,]
x = pygame.image.load ("images/a011.bmp")
frames = frames + [x,]
```

The variable **frames** is a list holding all of the images, and **frames[i]** is the i^{th} image in the sequence.

The building of the file name is interesting. It is common to use numbered names for animation frames (for example, *frame01* or *frame02*). In this case, the sequence is *a***.bmp*, where the *** represents a three-digit number. If the variable **i** is an integer, then **str(i)** is a string containing that integer, but the leading zeros are not present. Thus, for values of i between 0 and 9 (one digit) the string will be **"a00"+str(i)+".bmp"**; for values of **i** between 10 and 99 (two digits), the string is **"a0"+str(i)++".bmp"**; finally, for numbers between 100 and 999, the string will be **"a"+str(i)+".bmp"** (three digits). The leading zeros are manually inserted into the string.

The animation frames for the gait sequence are on the disk along with this code.

Example: Simulation of the Space Shuttle Control Console (A Class That Will Draw an Animation at a Specific Location)

Animations can sometimes be used to decorate a scene in interesting ways. A control panel showing video screens and data displays could use animations to fill the screens, giving the illusion of real things being monitored. A class that can play a frame-by-frame animation at any location on the screen could be instantiated many times, once for each display.

The class would have to read the frames it was to play and store them, play back the frames in a loop when requested, and place them within the window at any location. None of these tasks is especially hard. Code for reading frames from a file was written for the previous example, as was code for displaying the frames. Each class instance would need a frame count so that the loop could start over at the right place, and each class instance could have an animation with a different number of frames. Finally, placing at the right location is a matter of passing the correct parameters to the **image()** function. The class would be instantiated given the position as x and y coordinates of the upper left corner.

Sometimes, especially when multiple animations are playing, it will be necessary to slow down some animations so that they look right. The code calls **draw()** a fixed number of times each second, but that may not always be the correct speed for an animation. A count can be introduced so that the fame advances to the next only when a count exceeds a fixed delay value. If the count is 2, for example, then 2 calls to **draw()** are required before a new frame is chosen, meaning that the frame rate has been decreased by 50%.

This example implements a simulation of a space shuttle control console. This is a visual simulation, not one that allows interaction at any level, and we insert animations into a still photo of a real shuttle console and make it look more active. Figure 4a shows the static image that is used. There are many video screens visible, and the program being developed will replace the still image on some of those screens with moving, animated images.

Three of the screens are selected for animation. The image was displayed using Paint and the coordinates of the upper left corner of each of these screens was determined, as were the sizes. Figure 9.4b shows the location of these regions on the image.

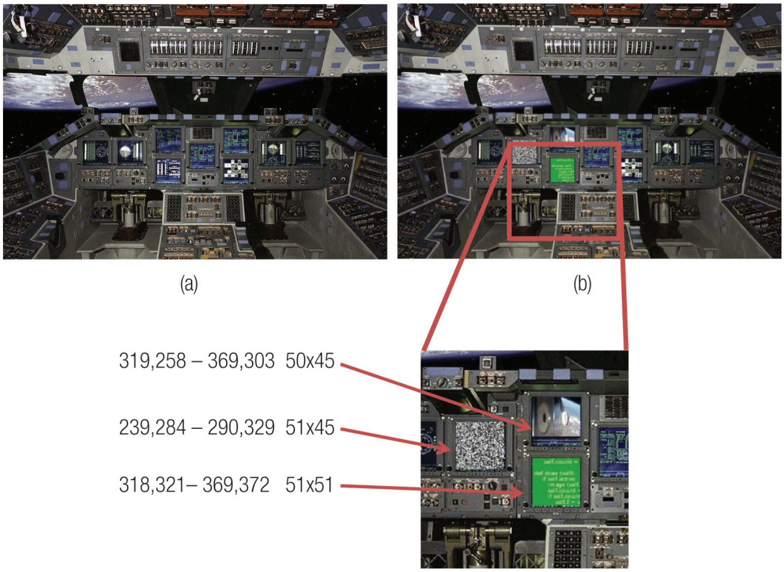


Figure 9.4
Images used for animation, from
https://commons.wikimedia.org/wiki/File:STSCPanel.jpg

The code for the class starts like this:

```
class Anim:
    def __init__ (self, x, y):
        self.frames = []
        self.xpos = x
        self.ypos = y
        self.n = 0
        self.f = 0
        self.active = False
        self.delay = 1
        self.count = 100000

    def draw (self):
        if self.active:
            screen.blit (self.frames[self.f],
                         (self.xpos, self.ypos))
            self.count = self.count + 1
            if self.count >= self.delay:
                self.f = self.f + 1
                self.count = 0
```

```
                if (self.f >= self.n):
                    self.f = 0
```

The part of the class that reads the frames as images is taken from the previous example:

```
def getframes (self, s1, s2):
self.frames = []
for i in range (0, 100):
    if i<10:
        s = s1 + "0"+str(i) + s2
        print ("Reading ", s)
    elif i<100:
        s = s1 + str(i) + s2
    try:
        x = pygame.image.load (s)
    except:
        self.n = i
        print ("Saw ", self.n, " frames.")
        break
    self.frames = self.frames + [x,]
```

There is a flag named **active** that determines whether the animations are currently running. The methods **start()** and **stop()** turn the animation on and off by toggling this variable.

```
def start(self):
          self.active = True

def stop (self):
          self.active = False
```

Finally, for this class, the delay can be set using a call to the **setdelay()** method, which simply changes the value of a class local variable **delay**.

```
    def setdelay (self, d):
        self.delay = d
The draw() method of the program simply draws the animations
by calling their respective draw() methods:

def draw ():
    a.draw()
    b.draw()
    c.draw()
```

The main program opens the window and loads and draws the background image:

```
background = pygame.image.load ("images/800px-STSCPanel.jpg")
screen.blit (background, (0,0))
```

The first animation, at x=239 and y=284, shows some television static, seven frames of which were created for this purpose using another program. A class instance is created to draw at (239,284) and **getFrames()** is called to load the images (the file names are "g100.gif" through "g106.gif"):

```
a = Anim(239, 284)
a.getframes ("images/g1", ".gif")
```

The second animation is at x=319 and y=258 and will display some exterior shots of the space shuttle. The process is the same as before, but the file names are "g200.jpg" through "g204.jpg." In addition, a delay of 100 is set, because these images are to be displayed for multiple seconds each to simulate a display scanning a set of cameras:

```
b = Anim (319, 258)
b.getframes ("images/g2", ".jpg")
b.setdelay(100)
```

Finally, the third animation, at x=319 and y=322, consists of a computer display showing Python code (this *class*, in fact). It was created by another program and consists of nine frames named "g300.gif" through "g308.gif." This animation is delayed a little as well so that it appears as if the text is scrolling properly:

```
c = Anim (319, 322)
c.getframes ("images/g3", ".gif")
c.setdelay(10)
```

The last step in the program is to start all of the animations playing:

```
a.start()
b.start()
c.start()
```

The example is complete on the disk and needs to be executed with the *images* directory, which contains the animation frames.

9.4 RGBA COLORS – TRANSPARENCY

In Chapter 7, we used transparency in an image to allow the visualization to "see through" to an image in the background. As it happens, any pixel can be assigned a degree of transparency that permits the same visual character. A color can be assigned a value that dictates how opaque or transparent it is, allowing colors behind it to influence how that pixel is seen. One can think of this as a fourth color value, in addition to red, green, and blue. It is referred to as *alpha*, and a color with four color parameters is said to be in the RGBA color space, for *R*ed, *G*reen, *B*lue, and *A*lpha.

If the value of Alpha is 255, then the color is opaque; as it decreases in value, the transparency increases until at Alpha=0, the pixel or object cannot be seen. A program that draws three overlapping circles using colors with an Alpha value of 60 shows the visual effect of using transparency (Figure 9.5a). Unfortunately, transparency cannot be specified simply by providing the Alpha value as a fourth value to the color tuple.

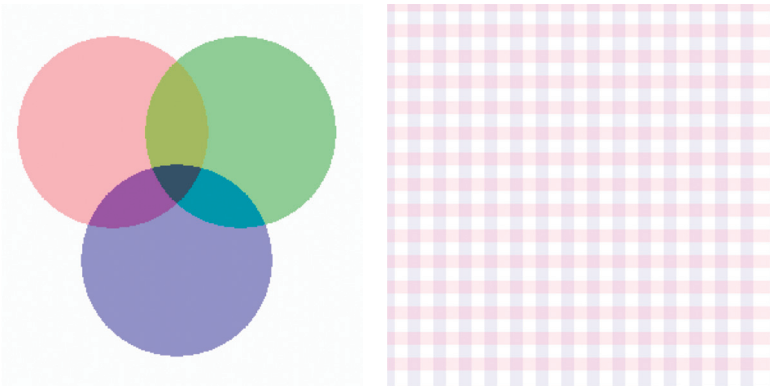
Transparency is partly a property of the surface on which the pixels are drawn. What we must do is create a new surface for the transparent item, set the transparency of that surface to the desired value, draw the item on that surface, and then **blit** it to the display surface. To draw three overlapping circles with different, transparent colors, this must be done three times, once for each circle. A draw function that does this is as follows:

```
def draw():
    s = pygame.Surface((300,300))
    s.set_alpha(50)
    s.fill((255,255,255))
    fill = (255, 0, 0)
    pygame.draw.circle (s, fill, (100, 100), 75)
    screen.blit(s, (0,0))

    s.set_alpha(50)
    s.fill((255,255,255))
    fill  = (0, 255, 0)
    pygame.draw.circle (s, fill, (200, 100), 75)
    screen.blit(s, (0,0))

    s.set_alpha(50)
    s.fill((255,255,255))
```

```
fill = (0, 0, 255)
pygame.draw.circle (s, fill, (150, 200), 75)
screen.blit(s, (0, 0))
```



(a) (b)

Figure 9.5
(a) Overlapping circles filled with transparent versions of red, green, and blue create new colors in the overlapping regions. (b) Stroke colors can have transparency, too. Where the red and blue lines intersect the red under the blue, it is seen as purple.

9.5 SOUND

Sound is an essential component of digital media. Proof? Almost nobody watches silent films anymore, and nobody makes them. Video games are rarely played with the sound turned off. There are a few important reasons for this.

1. Much human communication is through sound. Speech is the best example, but non-speech sounds, clapping, or stamping of feet are ways that people make their feelings and intentions known.
2. Sounds are associated with events. When an object falls to the floor, a sound occurs with the impact. A button is pressed and a doorbell rings. These sounds are important indicators.
3. Sounds cause emotional reactions in people. Music can do this; it can convey a mood better than almost anything else. But sound can also indicate things unseen: a growling in the dark; a screech in the sky; and the sound of an approaching vehicle around a curve in the road.

In Pygame, a sound is much like an image in terms of how it is used. A sound file is loaded and assigned to a variable, then that variable can be used to play, stop, rewind, and perform all audio operations on that sound. Each sound must be loaded into a distinct variable and has its own controls. The paradigm for sounds should therefore seem familiar.

The main sub-system in Pygame that deals with sound is named *mixer*. The first step in playing a sound is to create a mixer object and then use it to load the file. The function **pygame.mixer.Sound(s)** is used for this, passing the name of the sound file:

```
m = pygame.mixer.Sound("song.wav")
```

Playing the sound is done using the **mixer** method play:

```
m.play()
```

Example: Play a Sound

It's simple. A program that loads and plays a sound file is only 10 lines long:

```
import pygame
screen = pygame.display.set_mode((300, 300))
pygame.init()
FPS = 10
m = pygame.mixer.Sound("song.wav")
m.play()
while True:
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
```

Stopping a sound from playing is a matter of calling **m.stop()**. Setting the volume means calling **m .set_volume (v)** where the volume parameter v is between 0.0 and 1.0, where 0.0 is no sound and 1.0 is maximum volume. That's pretty much it for the basics.

Example: Control Volume Using the Keyboard

This example adds a volume control. The function **keypressed()** modifies the volume of the audio playback using the **set_volume** function. It changes the volume level by an increment each time the key "w" is pressed, and decreases it when the "s" key is pressed. The new program is as follows:

```
def keyPressed(k):
    global volume, m
    if k.key == pygame.K_w:
        volume = volume+.1
    elif k.key == pygame.K_s:
        volume = volume-.1
    if volume<0: volume = 0
    if volume>1: volume = 1
    m.set_volume(volume)
    print (volume)

screen = pygame.display.set_mode((300, 300))
pygame.init()
FPS = 10
m = pygame.mixer.Sound("song.wav")
m.play()
volume = 1.0
m.set_volume(volume)

while True:
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
        if event.type == pygame.KEYDOWN:
            keyPressed (event)
```

Example: Play a Sound Effect at the Right Moment: Bounces

A sound effect represents some event, and needs to be played at the moment the event happens. Synchronizing the two things is as simple as playing a sound when the event is detected. This example program plays a sound representing a ball hitting something when a simulated ball hits the side of the window and bounces. The bouncing ball animation program provides the impact event: when the ball hits the side of the window, the sound of an impact is played.

The sound effect is a file, and was recorded using an inexpensive microphone, a computer with a sound card, and the *Audacity* software, which is free and downloadable (see the end-of-chapter resources). The sound of a glass hitting a desk was recorded, edited, and saved as a ".wav" file named "bounce.wav." The program was modified to read that file, and then play it back whenever a collision with the window was detected. The program has three new lines of code, including the reading of the file:

```
m = pygame.mixer.Sound("bounce.wav")
.   .   .
def draw ():
    global dx, dy, x, y
    screen.fill( (200, 200, 200) ) # Erase the prior frame
    x = x + dx                     # Change ball position
    y = y + dy
    if x<=15 or x>=width-15:        # Bounce in X direction?
        dx = -dx
        m.play()
    if y<=15 or y>=height-15:       # Bounce in Y direction?
        dy = -dy
        m.play()
    pygame.draw.circle(screen, fill, (x, y), 15)
                                             # Draw the ball
```

In many situations, there can be a small delay between the event and the sound being played. A sound can rarely be played instantaneously.

Music

The **mixer.Sound** module is fine for many purposes, including playing music, but sometimes music has special needs and properties. Normally, only one music selection is played at a time. Sometimes, music needs to be paused and later restarted. For playing music, Pygame has a special module named **pygame.mixer.music** that has a different interface. First, there are no instances that are returned. Playing a song means loading it and then playing it like this:

```
pygame.mixer.music.load("song.wav")
pygame.mixer.music.play()
```

From this point on, references through pygame.mixer.music will affect the song that is playing. As before, the volume can be changed between 0 and 1:

```
pygame.mixer.music.set_volume(volume)
```

However, now the song can be paused and restarted:

```
    pygame.mixer.music.pause()
    pygame.mixer.music.unpause()
```

We can determine where the is playing at the moment, in milliseconds from the start, or set the posit at which it is to play:

```
pygame.mixer.music.get_pos()
pygame.mixer.music.set_pos(i)
```

There are other features documented at the Pygame website (*https://www.pygame.org/docs/ref/music.html*). A simple **keyPressed** function that allows the volume to be changed ("w" and "s") and the music to be paused and resumed ("p" and "r") is as follows:

```
def keyPressed(k):
    global volume
    if k.key == pygame.K_w:
        volume = volume+.1
        pygame.mixer.music.set_volume(volume)
    elif k.key == pygame.K_s:
        volume = volume-.1
        pygame.mixer.music.set_volume(volume)
    elif k.key == pygame.K_p:
        pygame.mixer.music.pause()
    elif k.key == pygame.K_r:
        pygame.mixer.music.unpause()
```

9.6 SUMMARY

Pygame can be used for displaying images and graphics. More media capabilities were explained, building on what has already been discussed, and we talked about sound and animations.

Using mouse position and button presses is a basic form of communication with a computer. The Pygame module keeps track of the mouse and continually updates the position available as the function call **mouse.get_pos()**, returning a tuple (**mouseX**,**mouseY).** If the user checks for the MOUSEPRESSED and MOUSERELEASED events in the main loop, mouse button presses can also be captured. A software graphical button is a rectangle or other area which, if the mouse button is clicked while the mouse cursor is within that area, will perform a task; in other words, the click while the cursor is in that area calls a function.

The keyboard is similarly dealt with by having the user check the KEYDOWN and KEYUP events in the main loop. The event contains a variable key gives the value of the key that was pressed as the parameter.

Animation is performed by rapidly displaying drawn images, or frames, one after the other, or by creating and drawing graphical objects and then changing their positions. A function named **draw()** can be written by the programmer to draw the frames many times each second.

Sounds are displayed by reading them from a file and calling a **play()** function when the sound is needed, using the mixer module. Sounds can be music, voice, ambiance, or sound effects.

Exercises

1. Write a program that determines how fast the mouse is moving (pixels per second assuming 30 frames per second) and displays that value.
2. Consider the example that prints a circle at a random position when a "+" key is pressed. Modify it so that when the "-" key is pressed the previous circle is deleted (no longer appears on the screen).
3. Write a program that reads lines from a file as pairs of x,y coordinates on a single line and draws them all. Each line would have four integers:

   100 100 200 200

   which are the (x,y) coordinates of the start and end points of the line. In the example above, the line would be drawn between (100, 100) and (200, 200).
4. Implement a circular button. It is represented on the screen as a circle at (100, 100) with the size of 30 pixels. Normally it is red, but it turns green when activated. When a mouse button is pressed while the button is activated, a rectangle is drawn somewhere (random) in the window.
5. Implement a button that normally has the text "Yes" drawn within it, but that changes that text to "No" when the button is activated. Pressing it does nothing.
6. Use Pygame to implement a text box that permits a file name or other text to be entered when the mouse cursor is within that region defined by the box. Use this to create a program that allows the user to enter a file name of an image and have the program display this image in the window.
7. Modify the program from Exercise 5 so that a sound is made when the button is pressed. A clicking sound would be most appropriate, but whatever it is, it must be of a short duration.
8. Floating point values, such as the current time of a song in seconds, are often converted into strings and require ten or more digits to be displayed. Write a function that changes a floating-point number so that it will display in five

digits, and modify the music display program so that all floats are displayed with only two digits to the right of the decimal.

Notes and Other Resources

Thanks to the estate of composer, musician, and friend Michael Becker for the use of the song *Holding On* and for the use of the .wav file.

Download for the *Pygame* module: *http://www.pygame.org/download.shtml*

An excellent sound editor for .wav and .mp3 files: *http://www.goldwave.ca/*

Another excellent sound file editor: *http://sourceforge.net/projects/audacity/*

Complete Pygame documentation: *https://media.readthedocs.org/pdf/pygame/latest/pygame.pdf*

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Chapter 10

Basic Algorithms

In this chapter

An algorithm, as discussed in previous chapters, is a step-by-step description of a means to solve a problem. As someone who is learning to program, what are the most important algorithms? That rather depends on how "important" is defined. Does it reflect commercial value? Number of times it is used? Pedagogical uses? Since there are many ways an algorithm can be important, this chapter deals with the most common algorithms discussed on programming Web pages and in introductory computing texts. None of these methods require a knowledge of advanced mathematics or data structures.

10.1 SORTING

Most people know what sorting is and can sort a small sequence of numbers in a few seconds. Each may have a distinct strategy for doing it, but few can explain to someone else how to sort an arbitrary set of numbers. They themselves may not know how they do it; they can simply tell when something is sorted, and have some process for sorting in mind. In short, the process of sorting is one of the simplest things that is hard to describe.

Because sorting is so important in computer science, it has been studied at great length. Sorting involves placing things in an order defined by a function that ranks them somehow. For numbers, ranking means using the numerical value. The sequence 1, 3, 2 is not in proper order, but 1, 2, 3 is in ascending (getting larger) order and 3, 2, 1 is in descending (getting smaller) order. Formally, a sequence **s** is in *ascending* order if **s**i <= **s**i-1 for all **i**. The act of sorting means arranging the values in a sequence so that this is true. It is clear that it can be decided when a sequence is sorted.

How can a sequence be placed in sorted order? By using a *sorting algorithm*, of course. For all of the following discussion on sorting, assume that the problem is to sort into ascending order.

10.1.1 Selection Sort

Small sequences are easier to sort than longer ones, and may provide some insight into the process. The sequence

8 4

is not sorted in ascending order, but testing this is easy and fixing it is trivial: simply swap the two values. The longer sequence

8 4 9

is also not sorted but is more difficult to sort because it is longer and there are more combinations of the numbers that are unsorted. How can this sequence be placed in order? Here's one idea:

1. Find the smallest element in the list.
2. Swap that element for the element at the beginning of the list.

3. Find the smallest element in the rest of the list.
4. Swap that element for the second element in the list.

   … and so on until the list is sorted.

This is called the *selection sort* algorithm, because at each stage, it selects the smallest of the unsorted items in the list and places it where it belongs. Consider the following list:

[12, 18, 5, 21, 9]
  0   1 2 3   4 - index

The smallest element in this list is 5, at index 2. Swap element 2 for element 0:

[**5,** 18, 12, 21, 9]

The bold elements above are in sorted order, which here is only the one at location 0. For the remainder of the elements, repeat the process of finding the smallest element and placing it at the beginning of the unsorted list (element 1). That means swapping 9 for 18, element 4 for element 1:

[**5, 9,** 12, 21, 18]

Repeating, it turns out that element 2, value 12, is now the smallest, and it is in the correct place.

[**5, 9, 12,** 21, 18]

Now the value 18 is smallest and should be placed at location 3.

[**5, 9, 12, 18, 21**]

Now the sort is complete. When only one remains, it must be in the correct place.

Finding the smallest element in a list involves three things. First, begin with the initial element and assume that is it the smallest. Identify it using its index **imin**. Next, check the value of all successive elements in the list (from **imin** to the end of the list) against the value at **imin**. Finally, in the case where one of the successive values at index **k** is smaller than the one at index **imin**, set imin to **k** to indicate where a new smallest value was found. In simple, imprecise English, scan all of the elements above **imin** and remember the location of the smallest one. Presuming that the list to be sorted is named **data**, the code for finding the smallest element from **imin** to the end of the list is as follows:

```
for i in range (imin, len(data)):
    if data[i] < data[imin]:
        imin = i
```

This code does work, but it modifies **imin**, which is used to determine the loop bounds, within the loop itself. This can be confusing. It is better to code this loop as:

```
imin = istart
for i in range (iend, len(data)):
    if data[i] < data[imin]:
        imin = i
```

What happens after this is to swap the smallest value found for the one at location **istart**. In most programming languages, this would take three statements, which would look something like this:

```
temp = data[imin]
data[imin] = data[istart]
data[istart] = temp
```

In Python, this swap can be performed using a different syntax:

```
(data[istart], data[imin]) = (data[imin], data[istart])
```

This is the core of the algorithm, and needs to be done for all values of **imin**; that is, from 0 to len(data)-1. This is another **for** loop within which this code is placed. The outer loop would be coded as follows:

```
for istart in range (0, len(data)-1):
```

This is all that is needed for the sort. Writing it as a function, it looks like this:

```
def selection (data):
    for istart in range (0, len(data)-1):
        imin = istart
        for i in range(istart,len(data)):
            if data[i] < data[imin]:
                imin = i
      (data[istart], data[imin]) = (data[imin], data[istart])
```

This sorting method appears to be natural to humans. It is the one most often described by students when asked how they sort numbers. It is not the fastest in many cases, but does a small number of swaps. If the data is already sorted, it does no swaps; if it is in reverse order, it does **len(data)-1** swaps, the smallest that can be done and still sort the list. When looking at algorithms, it is common to define a worst case and a best case, and to define performance not in seconds, but in terms of one of the operations performed. In that way the nature of the computer, whether it is fast or slow, does not affect the analysis. For sorting, it is common to select the operation to be used as a basis for comparison to be the compare operation: data[i]<data[imin]. How many of these are done?

The best case for the selection sort occurs when the list is already sorted. In that case, it will perform close to N^2 comparisons, where N = len(data). This is the same number of comparisons needed for the worst case, in which the list is in reverse order. At least it is consistent. However, it minimizes the number of times swaps occur, and if swapping is expensive, then this could be the sorting method to choose.

The selection sort is *unstable*. If there are repeated values in the data, then they will be together in the final, sorted list. However, if a sort is *stable*, they will remain in the same order they were originally. The selection sort does not guarantee this. It seems as if this is a minor thing, but it does matter in some cases. Consider a list of names in a list that are given, in order of some sort of score, on a Web page. Names for tie scores should always be in the same order on the page, so that if the page is refreshed or a link is followed, the page looks the same.

It should be said here that generally there is no best sorting method. The properties of such a method are as follows:

1. Fast. Selection sort is N^2 in terms of comparisons. The best one can normally expect from any sort would be N*log(N) in the worst case.
2. Does not need extra space. This means that the array can be sorted in place, with perhaps a temporary variable for performing swaps.
3. Performs no more than N swaps in the worst case.
4. *Adaptive*. The method detects when it is finished instead of looping through unproductive iterations. If, for example, such a method is given an already sorted list, it will finish in a single pass through the data.
5. Stable.

No method has all of these characteristics.

10.1.2 Merge Sort

Let's look at an algorithm that is different from the selection sort, and that has properties that it does not have. The method named *merge sort* fits that description nicely: it is an N*log(N) sort, it does need extra space, and it uses more than N swaps, but it is stable.

Merge sort is an example of a *divide and conquer* style of algorithm, in which a problem is repeatedly broken up into sub-problems, often using recursion, until they are small enough to solve; the solutions are combined to solve the larger problem. A merge sort breaks the data into parts that can be sorted trivially, then combines those parts knowing that they are sorted. Using the sample data from the selection sort example, the first step in the merge sort is to split the data into two parts. There are 5 elements in this list, and the middle element would be at 5//2, or 2, so the two parts are:

[12, 18]   [5, 21, 9]

Splitting again, the first set has 2 elements, the middle being at 0; the second set has 3 elements, so split at 1:

[12]   [18]   [5]   [21,1]

The final split breaks the data into individual components:

[12]   [18]   [5]   [21]   [1]

The splitting is done in such a way that the original locations are remembered. This happens in the recursive solution, but could be done in other ways. One way to visualize this is as a *tree* structure.

```
            [12, 18, 5, 21, 9]
             /              \
        [12, 18]          [5, 21, 9]
         /    \            /       \
    [12]      [18]       [5]     [21, 9]
                                  /    \
                               [21]    [9]
```

This completes the *divide* portion of the *divide and conquer*. Now that the individual elements are available, it is easy to sort them, as pairs. On the lower right the pair, [21] and [9] are out of order, so they must be swapped with each other. Now they are sorted. On the next level upwards, looking from left to right, the elements are sorted, although most are single elements:

```
                    [12, 18, 5, 21, 9]
                   /                  \
         [12, 18]                      [5, 21, 9]
        /         \                   /          \
   [12]           [18]            [5]            [9, 21]
```

Moving up again, [12] and [18] are combined to make [12,18], a sorted pair. On the right, the singleton [5] is merged with the pair [9,21] by looking at the beginning of each list and copying the smallest element of the pair into a new list:

Step	List 1	List 2		Merged list	
1	[5]	[9, 21]	→	[5]	5 is smaller than 9
2	[]	[9, 21]	→	[5, 9]	first list is empty, copy 9
3	[]	[21]	→	[5,9,21]	first list is empty, copy 21
4	[]	[]			Final list: [5,9,21]

The result is

```
             [12, 18, 5, 21, 9]
            /                  \
     [12, 18]                   [5, 9, 21
```

At each stage, the lists contain more elements and they are sorted internally, the smallest element at the beginning. Combining a pair of these is simply a matter of looking at the element at the beginning of each and copying the smallest one to the result until the lists are empty. The next, and final, merge in this set of data is as follows:

Step	List 1	List 2		Merged list	
1	[**12**, 18]	[**5**, 9, 21]	→	[5]	5 is smaller than 12, copy 5
2	[**12**, 18]	[**9**, 21]	→	[5, 9]	9 is smaller than 12, copy 9
3	[**12**, 18]	[**21**]	→	[5,9,12]	12 is smaller than 21, copy 12
4	[**18**]	[**21**]	→	[5,9,12,18]	18 is smaller than 21, copy 18
5	[]	[**21**]	→	[5,9,12,18,21]	First list is empty, copy 21

The final list is [5, 9, 12, 18, 21], which is sorted, as promised.

Once the data has been split into individual components, the merge stage creates sorted pairs, the next merge creates sets of 4 sorted numbers, the next 8, and so on, doubling each time until they are all sorted. A logical way to write the program is to use recursion, where each recursive call splits the data in two more parts until there is only one element. The lowest level of recursion combines the individuals into sorted pairs, and returns to the next level where the pairs are combined into fours, then eights, and so on, until at the highest level the list is completely sorted. Written as a recursive function this is

```
data = [12, 18, 5, 21, 9]
def mergesort (data):
    n = len(data)        # For this call there are n elements
                         # to be sorted
    if n <= 1:           # Divide the data into two parts
        return           # unless n-1, which means sorting
                         # is complete
    middle = n//2        # Index of the element in the middle
    lower = data[:middle]  # Lower indexes, or the left
                           # sublist
    upper = data[middle:]  # Larger indices, or the
                           # right sublist
    mergesort(upper)     # Sort the left sublist
    mergesort(lower)     # Sort the right sublist

# There are now two sorted sublists of length N//2.
# Merge them into one list of length N
    (i,j,k) = (0,0,0)
    while i < len(lower) and j < len(upper):
                                # One sublist may be shorter …
        if lower[i] <= upper[j]:# If the element at index
                                # i of the
            data[k]=lower[i]    # left list is smaller,
                                # copy it to the result
            i=i+1
        else:
            data[k]=upper[j]    # Otherwise copy the
                                # element at index j
            j=j+1               # of the right sublist
                                # to the result
        k=k+1                # Result gets longer by 1 element
```

```
    for i in range (i,len(lower)): # If the left list
                                   # was longer, copy
        data[k] = lower[i]         # the remaining items
                                   # to the result
        k = k + 1
    for j in range (j, len(upper)): # If the right list
                                    # was longer, copy
        data[k] = upper[j]          # the remaining
                                    # items to the result
        k = k + 1
```

The merge sort is not as obvious as was selection sort, but is faster in most cases. It has another interesting application: it can be used to sort files. If a file contains, for example, a billion data samples that need to be sorted it is unlikely that they can be read into memory and sorted with a selection sort. How then can we sort them?

10.2 SEARCHING

Searching is the act of determining whether some specific data item appears in a list and, if so, at which index. It seems like an odd thing to do; what can be done knowing this information? It is especially useful when multiple lists hold different data concerning the same items. An employee, as one example, might have their data saved as a name list, an employee ID list, phone number, office number, and home address. The same index gives information of the same individual for each list. Thus, search the employee ID list for 18762; if that index is 32, then the employee's name can be found at **name[32]**.

Of course, Python has built-in operations on a list that will do this:

```
if 18762 in employeeID:         # Is this ID a member of
                                # the list?
   k = employeeID.index(18762)  # What is the index of 18762?
```

A reason to examine searching algorithms is that not all languages possess these specific features and not all programs are written in Python. Another is that someone had to implement the operations for the Python system itself, and they had to know how. Are the built-in operations as fast as ones that a programmer could code for themselves?

10.2.1 Timings

Any section of code in Python requires some amount of time to execute. The specific amount depends on many things: the computer being used, the Python compiler, the specific statements, the data, and random events, such as what other programs are executing on that computer at the same time. However, if it is important to know whether a section of code is faster than another, there are timing functions that can provide a pretty good idea. The time module includes a function named **clock()** that returns (on Windows) the elapsed time expressed in seconds elapsed since the first call to this function. On Linux it behaves differently, and **time.time()** may be a better choice.

Timing a section of code is done by calling **time.clock()** before and after the code executes and subtracting the two times. For example, timing a search of a list using the in operator could be done in the following way:

```
import time

list = [19872,87656,10982,18756,56344,29765,12856,12534,
        88768,90012]
t0 = time.clock()
if 90012 in list:
    found = True
t1 = time.clock()
print ("Time was ", t1-t0)
```

This prints the message:

Time was 2.0628438804639O3e-05

That's a pretty small time, as is to be expected. When run again, the result was 3.07232e-06; running again gets 2.194514766e-06 and again 7.9002531e-06. These numbers are all small but very different. Since that is true, it is better to time many executions of the code and divide by the number of times it ran:

```
t0 = time.clock()
for i in range (0,10000):
    if 90012 in list:
        found = True
t1 = time.clock()
print ("Time was ", (t1-t0)/10000)
```

This yields more consistent results: 5.5284e-07, 5.5951e-07, and 5.415e-07 in three different trials. Averaging the result of multiple trials gives even better results, because spurious times on any one run will be averaged out.

10.2.2 Linear Search

Consider the list that was used in the timing example:

```
list = [19872,87656,10982,18756,56344,29765,12856,12534,
        88768,90012]
```

Finding whether the target number 90012 appears in this list is a matter of looking at each element to see if it is equal to the target. If so, the answer is "yes," and the index at which it was found is also known. This can be done using a basic **for** statement:

```
index = -1
for i in range(0,len(list)):
    if  list[i] == target:
        index = i
        break
# If the value of index is >= 0 then it was found.
```

This algorithm looks at each element asking "Is this equal to the target?" When/if the target is located, the loop ends and the answer is known. If the target is not a member of the list, then the algorithm has to examine all members of the list to determine that fact. Thus, the worst case is when the element is not in the list, and it requires N comparisons to find that out. If the element is a part of the list then, on the average, it will require N/2 comparisons to find it. It could be the first element, or the last, or any of the others, which averages out to N/2.

If the list is in sorted order, then the loop can be exited as soon as it is known whether the element is in the list. That is, as soon as the target is smaller than the element it is being compared against in the list, it is clear that it can't be a member of the list, and the loop can be exited. This normally speeds up the execution, but the penalty is that the list has to be sorted, and the time needed to do this (only once, of course) has to be taken into account.

10.2.3 Binary Search

If the list has been sorted then there is a faster way to search for an element. The list can be divided into two parts by looking at the value in the middle of the list and comparing it to the target. If the target is smaller than the middle element, then it would have to be in the lower indices (left), otherwise it would have to exist in a higher valued index (to the right). What this means for performance is that the search area is cut in half each time a comparison is done.

This idea seems simple, but is actually difficult to get right in an implementation. At conferences where many PhDs in computer science are presenting papers, it has been found that fewer than 10% of the participants can code a binary search that works the first time. The terminal conditions are tricky: in particular, how can it be determined that the target is not in the list? The details are crucial. At the beginning there is a list, and its length is known. The index of the middle element is known too, and the list is sorted. Find the index of the middle element:

```
istart = 0
iend = len(list)

m = (iend+istart)//2
```

If the target is in the list, is it at a smaller index than m (i.e., is **list[m]>target**):

```
if list[m]>target:
```

If so, don't bother looking at any index bigger than **m**. In other words, the largest index to look at would be **m-1**:

```
iend = m-1
```

If the target is in the list, is it at a larger index (i.e., is **list[m]<target**)? If so, don't look at any locations with an index less than **m**; in other words,

```
elif list[m]<target:
    istart = m+1
```

If **target = list[m]**, then it has been found and the algorithm terminates.

```
else:
    return m
```

This code has to be repeated until the target has been found, or it has been determined that it is not in the list. The loop condition is critical. The loop continues so long as **istart <= iend**, so that if the final step finds the target in the list, then it will return the index. If the loop exits without finding the element, then the index value is -1. The final code, as a function, is

```
def search (list, target):
    istart = 0
    iend = len(list)
    while istart<=iend:
        m = (iend+istart)//2
        if list[m]>target:
            iend = m-1
        elif list[m]<target:
            istart = m+1
        else:
            return m
    return None
```

The speed of the binary search depends on the fact that it is searching a randomly accessible data set like a Python list or a Java array, and not a file. It takes on the order of log(n) probes into the list to find what it is looking for or to determine that it is not there.

Timing the binary search gave an execution time of 3.305e-06 seconds, still slower than the built-in operation.

10.3 RANDOM NUMBER GENERATION

Python offers a random number module named **random** that offers a broad collection of random number generation facilities. How is it possible to generate a random number using software? Shouldn't a computer program execute consistently and always produce the same answer each time? Yes, it should. The resolution of this apparent problem lies is the definition of random.

First, randomness is defined only for collections of events or numbers. One number, or even a small collection, cannot be said to be random. Randomness reflects the *lack of a pattern*, and only one or two events don't really display a pattern. Randomness is more of a statistical property of a sequence and is not necessarily related strictly to unpredictability. After all, if a computer program can generate random numbers, then it should be possible to predict the next one it will generate.

A random number generator (RNG) on a computer is referred to as *pseudo-random*; it is not truly random, but exhibits properties of randomness. These properties can be tested statistically. A typical RNG returns a floating point number between 0.0 and 1.0. This value can easily be transformed into a random number, either real or integer, in any desired range. A die roll is an integer between 1 and 6 inclusive. An RNG function named rand01() can be converted into a die roll as

```
int(rand01()*6 + 1)
```

If the numbers generated by rand01() are random, then it should produce die rolls that each have a probability of 1/6. If not, then there is a bias.

If a coin is flipped many times and the sequence HTHTHTHTHTHTHT results, the probability of H or T (heads or tails) is 0.5, or 50%, which is what would be expected. If a sequence has the correct percentages for each outcome, then it passes the *frequency test*. Yet this sequence is probably not random because of the obvious pattern in the results. The frequency test is not enough.

A second test would consider pairs in the sequence and compare the probability of occurrence of each pair against the theoretical. In the coin toss, there are four possible pairs: HH, HT, TH, and TT. Each pair should appear with equal probability, and yet the string above shows only HT instances. It is not random. A standard suite of randomness tests called Diehard includes a more complex version of this test, involving groups of five elements in the sequence, each one having a theoretical probability of 1 in 120. This kind of test can be called the *serial test* or *overlapping permutations*.

A third test involves using the RNG to generate poker hands. The probability of specific hands is well-known, and any consistent variation from these probabilities would imply a flaw in the RNG. This is the *poker test*. Any complex random game could be used, and the Diehard suite uses the game of craps.

There are many other tests that could be applied, and all are based on generating complex situations and comparing the theoretical distribution of properties generated against what the RNG creates. So, now that there are ways of testing an RNG, can one be written in Python and tested?

10.3.1 Linear Congruential Method

Pseudo-random number generators basically shuffle the bits around in a number in complex and non-repeating ways; at least, they don't repeat for a large number of trials. A common method for doing this is to calculate a value that is bound to be larger than the place where it is to be stored and keep only the remainder each time. The value of this remainder is pseudo-random under certain conditions. A linear equation can be used and is fast to calculate:

$$X_{i+1} = (aX_i + b) \textit{ mod } m$$

where X_i is the previous random number in the sequence and X_{i+1} is the next one. The value of **m** should be quite large and it should be a prime number. Many computers have used a 32-bit integer size, and as it happens $2^{32} - 1$ is a good value for m (= 2147483647). Python integers can be as large as desired, so larger values could be used. Keeping then to 32 bits is accomplished using an *and* operation and masking the result with a 32-bit constant: `0xFFFFFFFF`**.**

Values for **a** and **b** are more flexible, but large values are a good idea, and too many factors can cause problems. One good set of values is **a=69069** and **b=362437**. This method uses a previous value to calculate the next one, so an initial value is required. This is called the *seed*, and it must be possible for a user/programmer to be able to set this seed value to whatever they choose. If not, then the RNG will generate the same set of values each time it is used. That's good for debugging, because when tracking down a problem, it is important that the program behave consistently.

The basic RNG described above is as follows:

```
_xseed = 76951

def irand01 ():
    global _xseed
    _xseed = (69069*_xseed+362437) & 0xFFFFFFFF
    return _xseed
```

This function returns a number between 0 and 2147483647, and resets the seed **(_xseed**, a global) each time. However, we need a function that returns a number between 0 and 1; a second function does this simply by dividing the above result by 2147483647:

```
def rand01():
    return irand01()/0xFFFFFFFF
```

A function that can set the seed is needed, too:

```
def setseed (x):
      global _xseed
      _xseed = x
```

A commonly used function in the Python *random* package is **randrange(a, b)**, which returns a random integer between **a** and **b**. The code for a die has already been written, and so the math is known. Using the tools just written, this is coded as

```
def randrange (n1, n2):
    x = (int) (rand01()*(n2-n1+1)) + n1
    return x
```

How can a random number generator be made to generate a different set of numbers every time a program starts using it? Simply by setting the seed to a number that is hard to predict. Such a number is found in the low bits (milliseconds and microseconds) of the system clock. It is impossible to predict what these will be. Randomizing the RNG can be accomplished like this:

```
def randomize ():
    global _xseed
    _xseed = int(time.time ()) & 0xFF
```

The **time.time()** function returns the number of seconds since a fixed date in the past, called the *epoch*. This date is usually January 1st, 1970, midnight.

Other methods for generating random numbers exist and are commonly used. Python's random class uses the *Mersenne Twister* algorithm, which is often seen as a default in programming languages, but is slow. The *Blum-Blum-Shub* algorithm resembles the linear congruential, but uses the relation **x**i+1 **= x**i2 **mod m** where **m** is the product of two prime numbers. Dozens more methods exist. There are also practical methods for generating true random numbers, and these are based on specific hardware that captures a truly random process such as radioactive decay, the photoelectric effect, or random electromagnetic noise.

Finally, there are websites that offer random numbers and sequences on request. *Random.org* serves up true random numbers, for example, and there are dozens of other such sites. The time needed to connect to a server and upload a random number is considerable, so they should be used knowing the tradeoff of time for the random number quality.

10.4 CRYPTOGRAPHY

Cryptography involves sending messages that only certain intended people can receive and understand. This involves *codes* and *ciphers*. A code substitutes one string for a longer message; there is a code book in which the code strings are associated with their relevant message. The string “A76” could mean “retreat 100 meters.” Code books had to be changed regularly because eventually one would fall into the hands of someone who was not supposed to have one.

A cipher is an algorithm that converts one string of characters into another one of generally the same length. It can operate on bits, on characters, or on blocks of characters. A cipher does not have a code book but does have a key, which is a string of numbers or characters, that the algorithm uses to transform the original string (called the *plaintext*) into the encrypted string (called the *ciphertext*). The ciphertext can be transmitted safely because it cannot be understood without the key.

Cryptography has become much more important in the last 30 years or so. It’s not just that the world is an uncertain place. It is more that people wish to share private information across the Internet. If a purchase is made with a credit card, then the card number should be encrypted before sending it to the seller. Access to certain sites that have valuable services or information requires a password. Installing new software requires an access key. These are all examples where encryption is required.

It should be mentioned that the secure transfer of information depends on *operational security* as well as on encryption. Someone with a password can access all services and data associated with that password, so keys and passwords must be protected. This aspect is beyond the ability of a programmer to control, and is often the way security systems are broken.

There is some terminology that needs to be understood. A *symmetric key* system uses one key to encode and the same key to decode. *Asymmetric* systems like *public key* systems use one key to encrypt the message, a key that anyone can know, and a second, private key that only the recipient knows and is used to decrypt. A *block cipher* applies a key to a collection (block) of data, often a size of 64, 128, or 256 bits at a time. A *stream cipher* is usually a symmetric key cipher that encrypts a plain text character with a character from the key. It’s also called a *state cipher* because the encryption of the next character depends on what has happened before.

Knowing a little about encryption is important, but it is also important to understand that it is a very complex and highly mathematical subject, and requires a significant amount of study to become an expert.

10.4.1 One-Time Pad

Having just said how complex the field of cryptography is, the first algorithm to be examined is, in fact, rather old and perfectly secure, if difficult to use in practice. Suppose person A wishes to send person B the message “Meet you at nine pm at location alpha.” Encoding this requires a sequence of random characters at least as long as the message. In actual use, this cipher often used pages from books as keys, books that were easily accessible by both parties. In this case the following text is used as the key: “it was the best of times, it was the worst of times.” The encryption process, known to both, and in fact not really a secret, is to apply the exclusive OR operation to corresponding characters in the message and the key to produce the ciphertext:

```
m   e   e   t   y   o   u   a   t   n   i   n   e   p   m   a   t   l   …   Message
i   t   w   a   s   t   h   e   b   e   s   t   o   f   t   i   m   e   …   Key
4   17  18  21  10  27  29  4   22  11  26  26  10  22  25  8   25  9   …   Encrypted
```

The exclusive OR operation is a bit-by-bit logical operator that is 0 if the two bits are equal and is 1 otherwise. It is applied to the numerical representations of the characters. This is quite handy because it is very fast and can easily be accomplished using simple hardware. Consider the first character in the message “m.” The first character in the key is “i.” The ASCII codes are the numbers 109 and 105, respectively, or in binary, this is

0 1 1 0 1 1 0 1	109	“m”
0 1 1 0 1 0 0 1	105	“i”
0 0 0 0 0 1 0 0	4	Exclusive OR

One interesting observation here is that different characters can be encrypted to the same cipher text byte, as in the above string where “s” and “t” both encrypt to 26. Now, this ciphertext is transmitted to B and is decoded in exactly the same way that it was encoded: apply the exclusive OR between the ciphertext and the same key (symmetric key):

```
4    17  18  21  10  27  29  4   22  11  26  26  10  22  25  8   encrypted
i    t   w   a   s   t   h   e   b   e   s   t   o   f   t   i   Key
105  116 119 97  115 116 104 101 98  101 115 116 111 102 116 105 Key ints
109  101 101 116 121 111 117 97  116 110 105 110 101 112 109 97  XOR
M    e   e   t   y   o   u   a   t   n   i   n   e   p   m   a   Decrypted
```

The Python code that can do the basic encryption is as follows:

```
pt = "meetyouatninepmatlocationalpha"
key = "itwasthebestoftimesitwastheworstoftimes"
ct = ""
xt = ""

for i in range(0,len(pt)):
    v = ord(pt[i])^ord(key[i])
    print(v)
    ct = ct + chr(v)
print (ct)
```

The exclusive-OR operator is "^," and the expression **ord(pt[i])^ord(key[i])** performs the XOR on the message and the key bytes, as numbers. Doing it again with the same key gets the message back.

The reason that this is called a *one-time pad* is that the key can only be used once, otherwise the cipher is not secure. The security lies in the randomness of the key, and reusing it reduces the randomness. Eventually, if the same key is used often enough, an observer, someone who can intercept all of the messages, can extract the pattern and determine the key. In practice, the keys were written on pads of paper and, once used, were destroyed. Keeping the pads synchronized between the sender and receiver can be a problem, especially if there are many of each. Hence, although the system is secure, it is not used very often.

10.4.2 Public Key Encryption (RSA)

A public key system is commonly used for secure communication across computer networks, and involves one key for encryption and another for decryption. There are many variations on the basic idea, some being much too complex to discuss in a few pages, but the RSA algorithm is relatively simple, quite popular, and very secure. It is named for its inventors **R**ivest, **S**hamir, and Adleman.

The mathematical idea that underlies RSA is that one can find three very large integers **e**, **d**, and **n**:

$$\left(m^e\right)^d \bmod n = m$$

for any **m**, and that even knowing **e** and n or even ***m***, it can be extremely difficult to find **d**. The values **d** and **e** are the keys, and **m** is the message.

Encrypting a message would work as follows: A sends message m to B using B's publicly known encryption key e:

$$c = m^e \bmod n$$

The value of **c** is the ciphertext and can be transmitted to B. When B receives the message, it is decrypted using their private key d:

$$m = c^d \bmod n$$

where n > m. This works because of the original assertion that **(me)**d **mod n = m**. The success of this method depends on a few other things: can **c**d **mod n** be calculated quickly enough for large numbers (i.e., 500 bits), and can the numbers **d**, **e**, and **n** be found to make this work?

The first step in determining the keys is to select two very large prime numbers, **p** and **q**. Let **n = p*q**. A *large* number in this context has hundreds of bits, but that creates a cumbersome example, so smaller numbers are used in this discussion.

Now calculate **j(n) = (p-1)*(q-1)** and find an integer **e** so that **e** and **n** are co-prime; that is, the greatest common divisor between **e** and **n** is 1.

Let d = (e-1) mod φ(n) so that d*e mod n = 1. This can be found using a search, which may be infeasible due to the size of the numbers:

```
for i in range (e, n):
    if (i*e)%j == 1:
        d = i
        break
```

ON THE CD

A mathematical process that uses Euler's theorem can give the answer faster, and code has been provided for this on the accompanying disk.

10.4.3 Example: Encrypt the Message "Depart at Dawn" Using RSA

The first step is to determine some keys to use and to distribute the public key. Using the prime numbers 73 and 83 (far too small for a real situation), the determination of the keys is as follows:

n is 6059 and j(n) is 5904

e is 17, chosen because it is prime. Now find d such that d*e mod n = 1. Searching for it is practical for numbers this size and one gets the following result:

$$d = 3473$$

The public key is (17 , 6059), and the private key is (3473).

The message is 14 characters long and is 112 bits; n is only 10 bits long, and the message has to be shorter than this. In this instance, the message can be sent one character at a time, but this is generally poor practice. Normally, larger blocks of data are encrypted at one time. The plaintext string is converted into integers using **ord**(), and each one is encrypted using the formula

$$c = m^e \bmod n$$

An example is

```
message = "Depart at dawn"
imessage = ()
cmessage = ()
for i in range (0, len(message)):
    m = ord(message[i])
    imessage = imessage +(ord(message[i]),)
    c = (m**e) % n
    cmessage = cmessage + (c,)
```

Now the message consists of 14 blocks of 1 character each. It can be transmitted to the recipient, who is normally named B or Bob, in this form. The sender, named A or Alice, had access to the public key only, which is all that is needed to encrypt the message. It cannot be decrypted using the public key.

d given $d \cdot e \equiv 1 \pmod{\varphi(n)}$

Bob receives the ciphertext message, which is

(4652, 3518, 4274, 5770, 1663, 344, 2498, 5770, 344, 2498, 2144, 5770, 1725, 4601)

He takes each block and decrypts it using the following formula:

$$m = c^d \bmod n$$

The Python code for this is

```
dmessage = ()
for i in range (0, len(cmessage)):
    c = cmessage[i]
```

```
    m = (c ** d) % n
    dmessage = dmessage + (m, )
```

The resulting decrypted message is

(68, 101, 112, 97, 114, 116, 32, 97, 116, 32, 100, 97, 119, 110)

which is the original message. Notice that because only one block per character was encrypted, the effect is that of a substitution cipher, in which each letter has been replaced by another. This is very easy to decrypt by noting patterns of letters and frequencies of letters in the language; the letter "e" is usually the most commonly used letter in an English message. That is why the message is encrypted as blocks of characters. It is highly unlikely that a large block would be repeated exactly, and if it were it would be difficult to guess what it was anyway.

10.5 COMPRESSION

Let's use a little arithmetic to start this discussion. The song "Blackbird" by The Beatles is almost exactly 4 minutes long. This is 240 seconds, and if it was converted into digital form, it would be sampled at a rate of 44,100 samples each second. This means that the song has 240*44100 = 10.6 million samples. But wait—it's stereo, so double that number to 21.2 million samples. A typical sample is 16 bits, so this works out to 42.4 million bytes: 42 megabytes. The MP3 file for this song is typically 1.9 megabytes. How is that possible? By using a *compression* algorithm.

Figure 10.1
Sample image for compression.

Data compression is all about ways to take, for example, 100 bytes of information and turn it into 10 bytes while losing none of the essential message. Of course, compressed data is incomprehensible just to look at and must be decompressed in order for it to be used. Data is often compressed before storing it in a file to reduce its footprint on the storage device, or before transmitting it along a communications channel to take better advantage of limited bandwidth.

The question of how a string of data bytes can be made shorter while losing no important information remains, and a simple example may be in order. Consider a cartoon image. These have a relatively small number of distinct but vivid colors, usually less than 10 colors and the color variation within any region is small. The example image in Figure 10.1 is in PNG form and is 23.2 Kbytes in size at 400 x 456 (= 182400) pixels. As raw data it would be a little over 182 Kbytes in size, and it would be 547 Kbytes if RGB color was used.

A simple compression technique that works is called *run-length encoding*. In its simplest form, data bytes are preceded by a count indicating how many repetitions of that value were encountered in the data. If there was a section of data as follows:

1 1 0 0 0 0 0 0 2 2 2 1 2 1 2 0 0 0 0 0 2 2 2 2 2

This section of data would be encoded as

2 1	6 0	3 2	1 1	1 2	1 1	1 2	5 0	5 2
Two	six	three	a	a	a	a	five	five
ones	zeros	twos	one	two	one	two	zeros	twos

In this case, the original data required 26 bytes and the compressed data required 17 bytes. The new data takes 65% of the space that the original does. This is not a large savings, but is probably worth the effort. It does depend heavily on the nature of the data.

Consider the image of Figure 10.1. The color areas are uniform and rather large, so this image would be an ideal candidate for run-length encoding. When writing the program, it is important to use a binary file and convert the value and count into unsigned bytes before writing them to the file. This is a new data type called an *unsigned byte* that was not discussed in Chapter 8, and it has the code "B." Writing the count and value could be done in the following way:

```
s = pack("BB", n, v[1])
     f.write(s)
```

The entire program run-length encodes the image, reads the image file, and collects identical pixels, counting them as they are collected, until a change in the pixel value occurs. Then the (count, value) pair is written to the file. The pair is written if 255 pixels have been collected, since that is the biggest number that can be counted in 8 bits. The result is a binary file of pairs of numbers (count, value) that represent the pixels in the image. As there are only two colors, the value can be 0 or 1, 0 being white and 1 being green; in general, there can be 256 distinct values. The encoding program looks like this:

```
from struct import *
import pygame

def emit(v, n, f):
    s = pack("BB", n, v[1])
    f.write(s)
b1 = pygame.image.load ("b1.png")
sz = b1.get_size()
width = sz[0]
height = sz[1]
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 10

outf = open ("b1.txt", "wb")
count = 0
value = b1.get_at((0,0))
for j in range (0, height):
    for i in range (0, width):
       if count ==255:            # Largest possible count.
            emit (value, count, outf)
            count = 0
        c = b1.get_at((i, j))
        if c == value:             # Same as before
            count = count + 1
        else:
            emit(value, count, outf)
            count = 1
            value = c
if count>0:
    emit (value, count, outf)
outf.close()

while True:
    clock.tick(FPS)
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()

    screen.fill((180, 180, 180))
    screen.blit(b1, (0,0))
    pygame.display.update()
```

The decoding program reads pairs of unsigned bytes from the binary file, and creates pixels. A pair (12, 0) would be 12 white pixels, for instance. A pair (12, 1) could be 12 pixels of some other color, and this program writes the pixels so it decides what color that will be. It will read pairs and draw pixels, into an image of 400 columns and 456 rows, until all are accounted for. A program that does this (not the only one possible) is

```
inf = open ("b1.txt", "rb")
i = 0
j = 0
cols = 400
rows = 456
screen = pygame.display.set_mode((cols, rows))
clock = pygame.time.Clock()
pygame.init()
FPS = 10

while True:
    s = inf.read(2)
    if len(s) <= 0:
        break

    c,v = unpack("BB", s)
    print (c, v)
    if v == 255:
        clr = (255, 255, 255)
    else:
        clr = (123, 210, 0)

    for k in range (0, c):
        if i >= cols:
            i = 0
            j = j + 1
        screen.set_at ((i,j), clr)
        i = i + 1
    if j>= 456:
        break


while True:
    clock.tick(FPS)
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
    pygame.display.update()
```

The more complex the data is, meaning the more distinct values the data can take, the less useful this encoding method is. In some cases, it can make the file size *larger* that the raw data would have been. In the case of this particular image, the run-length encoded file is about 6 K bytes, as opposed to half a million bytes that would have been needed for the raw image, saved as pixels. Still, this serves as proof that it is possible to compress a data file without losing any information. There are, of course, many more algorithms that compress data to a greater extent and with fewer constraints.

10.5.1 Huffman Encoding

If a typical text file is examined carefully, the vast majority of the file consists of relatively few characters. As a general estimate, over 95% of the characters can be accounted for by between 25–30 distinct values. A coding scheme that took this into account would reduce the size of a text file, and perhaps it would generalize to other kinds of file. For example, in many files, the value 0 is the most common, and giving it a smaller representation than, say, 9 may reduce the overall file size.

This is not really a novel idea. The international Morse code is based on this idea and has been around for a long time, beginning in 1836. The most commonly used letters in English are shown in Table 10.1. In the Morse code, the letter "E" is represented by a single dot, the letter "T" is a single dash, and "A" is a dot followed by a dash. The most common letters have the smallest code representation, as a general rule. This is how the Huffman code is organized, too.

Table 10.1
Frequency of Letters in English text

Letter	Frequency %	Letter	Frequency %	Letter	Frequency %	Letter	Frequency %
E	12.5	R	6.1	F	2.3	K	0.7
T	9.3	H	5.4	P	2.0	X	0.19
A	8	L	4.1	G	2.0	J	0.16
O	7.6	D	4.0	W	1.9	Q	0.11
I	7.3	C	3.1	Y	1.7	Z	0.09
N	7.1	U	2.7	B	1.5		
S	6.5	M	2.5	V	1.0		

A Huffman code is constructed from the ground up, like a wall. The lower levels of the wall represent the least frequently used symbols, and have the greatest number of bricks above them. The final code includes binary numbers, and the length of the code in bits for a symbol is related to the number of bricks above it. The wall is shaped like a pyramid, and is called a *binary tree*. It's a very useful structure in general, but the description is restricted here to its use in Huffman codes.

As an example, consider the English text:

I think that at that time none of us quite believed in the Time Machine[11]

The characters occur in this particular text with the following frequencies:

t	10	a	4	q	1	k	1
e	9	m	3	c	1	s	1
i	8	o	2	d	1	l	1
n	5	u	2	v	1		
h	5	b	1	f	1		

The "leaves" (or *nodes*) at the bottom of the tree (it is drawn upside-down) contain the lowest frequency items, and so are placed first. Each two nodes in the tree have one node above them, straddling them, containing the sum of the frequencies of all nodes below. All characters are turned into nodes, and each also contains the number of occurrences of that letter. This collection of nodes is called a *heap*. Initially, all have only one character, but this changes.

The rule in building the tree is to pick the pair of nodes (initially characters) that sum to the smallest number and connect them using another node, one above them that has a left and right node. The first bricks, alphabetically, are "b" and "c," both with a frequency of 1.

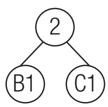

Figure 10.2
A step in the Huffman algorithm, lowest level

The bottom nodes have characters and counts. The one above has only a count, and it is the sum of the counts of the two nodes it is connected to. This new node, with a count of 2, is placed back in the heap and the nodes for B and C are removed. The heap always gets smaller.

Repeating this process with the others, the smallest pair we can make is with "d" and "f," then "k" and "l," and then "q" and "s." At that point, the smallest node is "v" with a count of 1, but there are no more nodes with a count of 1. The smallest sum is 2, which uses "v" and "o."

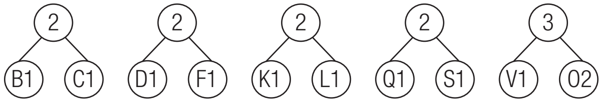

Figure 10.3
The complete Huffman bottom level

All of these are in the heap, and a search is done for the smallest sum of nodes. The character "u" has a count of 2 and so do any of the nodes above that link to two other characters. These are nodes too, so link "u" with the leftmost node above to get a bigger grouping—this is called a *subtree*, because it is a tree, but it is also part of a bigger tree.

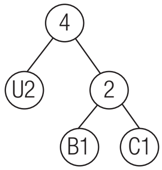

Figure 10.4
The first 3 deep tree section: U B C

The "u" node and the others give a sum of 4.

The tree that is being built has the least commonly used characters placed at a greater distance from the top of the tree than are the frequently used characters. This distance is used to construct the codes, smaller for common characters.

The smallest sum of two nodes in the tree is 4, the nodes connecting "d," "f," "k," and "l."

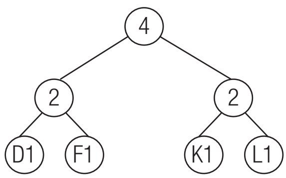

Figure 10.5
The next step in the Huffman algorithm: D F K F

The method takes the smallest two nodes, which are going to create the smallest sum, and connects them, removing the original nodes and replacing them with the new one. The smallest nodes now are the node connecting "q" and "2" (value 2), the node with "m" (value 3), and the node connecting "v" and "o" (value 3). The node with "m" will be selected to link to the 2-valued node. The tree is a disconnected collection of nodes.

So, what's next? The smallest valued character remaining is "a" at 4. That would make the smallest sum 7 after connecting it with the subtree on the right ("v" and "o"). Next in the heap are the two 4-nodes above to create an 8, and linking "h" (5) and "n" (also 5) to get a 10.

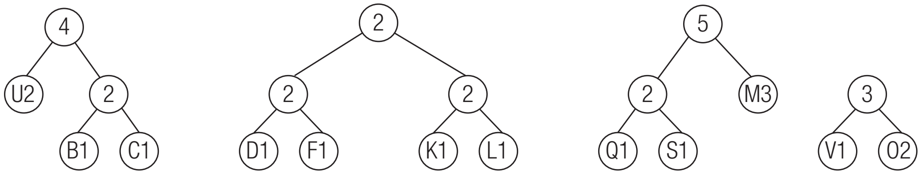

Figure 10.6
Three lower levels complete

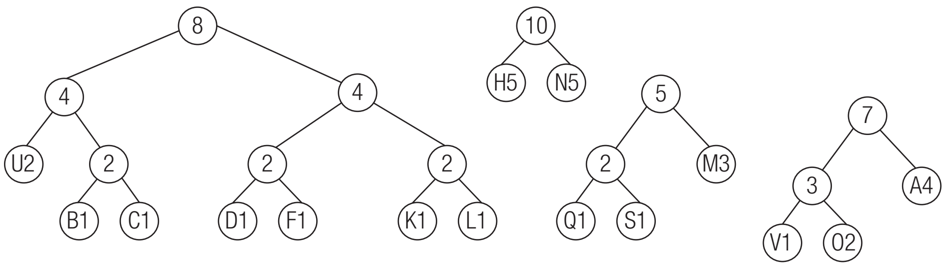

Figure 10.7
The next level of the Huffman tree complete.

The pattern should be clear by now. Notice that the nodes with nothing below them always consist of characters, and the nodes above have only numbers. However, the space characters were not counted, and they must be for the message to make any sense. There are 14 spaces in the message. The final sum is 14+9 for the space. A node for a space has to be added to the heap.

The last two steps don't involve any new characters, but they will link all of the nodes together and make them accessible from one single node at the top. The final (top) node should have a value that is the length of the original string.

The tree that has been constructed will be used to construct the codes for each letter, and the length of each code is the number of nodes between the

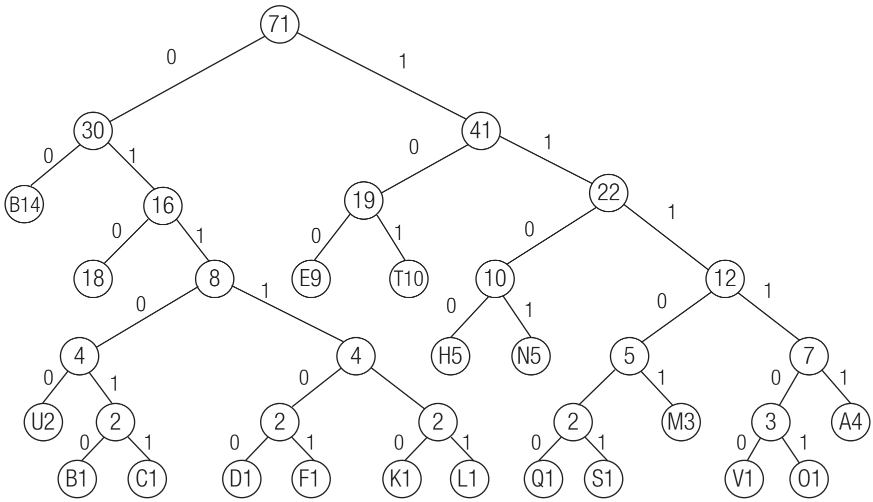

Figure 10.8
The final tree

characters and the top (*root*) of the tree. The path to each left node is labeled with a digit, in this case a 0, and the path to the right nodes is labelled with a 1, as in the tree above. The code for any character is read off of the links that were followed to get from the top of the tree to the node containing the character. The space character, the most common one, is reached by going left two times; its code is 00. The "t" is the second most frequent character, and is reached from the top node by going right, then left, then right; the code is 101. The complete set of codes is as follows:

' '	00	A	11111	D	011100	V	111100
T	101	M	11101	F	011101		
E	100	U	01100	K	011110		
I	010	O	111101	L	011111		
H	1100	B	011010	Q	111000		
N	1101	C	011011	S	111001		

The coded message is the concatenation of all of the codes for the characters in the order they appear in the message. The encoded message is as follows:

i t h i n k t h a t a t
010 00 101 1100 010 1101 011110 00 101 1100 11111 101 00 11111 101 00

```
 t  h     a      t        t   i   m     e        n    o     n      e
101 1100 11111 101 00 101 010 11101 100 00 1101 111101 1101 100 00
  o      f         u        s           q    u    i    t    e        b
111101 011101 00 01100 111001 00 111000 01100 010 101 100 00 011010
 e      l    i     e      v     e     d        i   n       t    h     e
100 011111 010 100 111100 100 011100 00 010 1101 00 101 1100 100 00
 t    i     m    e        m     a      c     h    i     n    e
101 010 11101 100 00 11101 11111 011011 1100 010 1101 100
```

This amounts to 259 bits = 33 bytes. The original string is 71 bytes long, so the compressed data is 46% of the size of the original data. The Huffman coded string is broken into 8-bit bytes and transmitted that way:

```
01000101 11000101 10101111 00010111 00111111 01001111
11010010 11100111 11101001 01010111 01100001 10111110
11101100 00111101 01110100 01100111 00100111 00001100
01010110 00001101 01000111 11010100 11110010 00111000
00101101 00101110 01000010 10101110 11000011 10111111
01101 110 0 010 1101 100
```

Decoding requires the table or the tree. If a known table is used, such as the natural frequencies of English letters, then it would not have to be transmitted along with the message. The use of a Python *dictionary* type makes the program for decoding very elegant indeed. Given the table and the message, bits are removed from the beginning of the message and placed into code string until they match one of the codes in the table. The Huffman code has the property that the bit sequences are unique when appended as a long message. The first bit sequence that matches a code is the code for the first letter in the message.

```
# Huffman decode
# This is the coded message:
bitstring = "01000101110001011010111100010111001111110100111111"+\
"01001011100111111010010101011101100001101111101110110000111110"+\
"1011101000110011100100111000011000101011000001101010001111101"+\
"0100111100100011100000101101001011100100001010101110110000111"+\
"0111111011011110001011011 00"
table = {}                    # This is the table of codes
table['00']     = " "
table["11111"]  = "A"
table["011100"] = "D"
table["111100"] = "V"
table["101"]    = "T"
table["11101"]  = "M"
table["011101"] = "F"
table["100"]    = "E"
```

```
table["01100"]  = "U"
table["011110"] = "K"
table["010"]    = "I"
table["111101"] = "O"
table["011111"] = "L"
table["1100"]   = "H"
table["011010"] = "B"
table["111000"] = "Q"
table["1101"]   = "N"
table["011011"] = "C"
table["111001"] = "S"

# Pull bits from the string making a substring until the
# substring is found in the dictionary. Then emit the
# character indexed.

# Loop until all bits are used
while len(bitstring) > 0:
    code = ""                        # Clear the current code
                            # While code NOT in the dictionary …
    while not (code in table):
                            # Add the next bit from the message
        code = code + bitstring[0]
                             # Remove that bit from the message
        bitstring = bitstring[1:]
# When the code matches, print the character corresponding to the
code
    print (table[code], end="")
```

10.5.2 LZW Compression

Like many algorithms, LZW compression is named after the people who devised it: A. Lempel, J. Ziv, and Terry Welch. It has been the standard for data compression for many years, it was the method used in the GIF file format, and it was used in many versions of PDF. It is not the most effective method of compression, but it is lossless and efficient. Like the Huffman code, LZW creates a table from the original text and uses the codes in the table to perform the compression. Unlike the Huffman code, the decompression stage does not require that the table be known in advance; it builds the table as it decompresses the file. The LZW algorithm also replaces multiple characters with single codes, thus increasing the compression rate.

LZW compression usually begins with a known code table, most often the 256 ASCII characters, but any table known by the compressor and decompressor will work. As an example, another short section of text from *The Time Machine* will be compressed.

> The Time Traveller for so it will be convenient to speak of him was expounding a recondite matter to us His grey eyes shone and twinkled and his usually pale face was flushed and animated The fire burned brightly and the soft radiance of the incandescent lights in the lilies of silver caught the bubbles that flashed and passed in our glasses.

Punctuation has been removed for simplicity. The algorithm begins with a table of characters, in this instance, the ones that appear in the quote, but in general, the table can contain any starting set of symbols. This is called the *code table*, and associates a numerical code with a string. The code table in this case consists of the letters (uppercase) and their values starting with 0: A=0, B=1, and so on. The space has to be included as well. The code sequence 024 is the string "ACE" using this scheme.

Naturally, there has to be more to this if it is to be a viable compression method. When encoding, the characters are examined one at a time and appended to an input string, and looked up in the table. If the string is found in the table, then the next character is read and appended to the string and it is looked up again. This repeats until the string is not found, at which point a few things happen: the code for the last string that was found is written to the output, the new string that was encountered in the string but not found in the table is added to the tables, and the process continues using the last character read in. This means that not only characters, but also short strings that occur in the text have numeric codes, and that the table will be created from the text that was given.

Consider the text in the example: The first character seen is "T."

1. "T" exists in the table already, so a new character is read in and appended to the "T" to create the pair "TH."
2. "TH" is *not* in the table. The character "T" has the code 19, so 19 is written to the output file.
3. The string "TH" is added to the table. It will be code 27.
4. The input string is now "H."
5. The character "H" is in the table and has code 7. The next character is read in and appended to "H," creating "HE."

6. "HE" is not in the table, so the code for character "H," which is 7, is written to the output file.
7. The string "HE" is added to the table, code 28.
8. The input string is now "E."

The process repeats. If a multiple-character string is found in the table, then the steps are basically the same. Hypothetically,

1. The character "T" is next and is in the table. Read the next character "H" and append to "T" to get "TH."
2. "TH" is in the table. Read the next character "E" and append to "T" to get "THE."
3. "THE" is not in the table to emit the code for "TH," which is 27.
4. Input string is now "E."

Step 1 repeats until a string is obtained that has not been seen before. In the example here, the first 27 codes are letters and the space character. The next few codes are as follows:

TH 27	HE 28	E 29
T 30	TI 31	IM 32
ME 33	E T 34	TR 35

The first 3-character string (*trigram*) in the table is "E T."

Python's dictionary type is especially valuable for coding the LZW algorithm. The facility for looking up a string in a table is exactly what is required here. The critical part of the program could be written as follows:

```
# count is the next unassigned symbol
# ch is the last character read in
# s is the current character string
# inf is the input file (text)
s = ""                     # Initial string is empty.
ch = inf.read(1).upper()   # Read the first character,
                           # upper case.
while len(ch) > 0:         # While the file still has data …
    if s+ch in dict:       # Is string concatenated with
                           # ch in the table?
        s = s + ch         # Yes. Concatenate and repeat
    else:                  # No.
        print (dict[s]," ", end="")  # Print the code
```

```
                                         # for the string s
        dict[s+ch] = count           # Put the new string into
                                     # the dictionary
        count = count + 1            # New code is next integer.
        s = ch                       # String is now the last
                                     # character read.
    ch = inf.read(1).upper()         # Read a new character
```

When decoding the LZW file, the initial table is known. Again, this is often just the ASCII characters, but can be something else, and in this case is the letters plus the space. The file contains codes, not characters, but the codes are in the table, right? No, only the starting codes are in the table. Decoding the message in the example starts easily. The first few codes in the message are as follows:

19 7 4 26 19 8 12 29 19 17 0 21 …

The first code is read in and is the code for the letter "T." This is followed by 7 (H) and 4 (E) and so on until the code 29 is reached. There is no entry for the code 29 in the table. This is where the really clever part of the LZW algorithm happens.

When decoding, *the program builds the table again*. After all, the characters are in the same order in the encoded data, so it should be possible to reproduce the process that was used to build the code table in the first place. When the first code is read in, the code is expected to be in the table, and the corresponding letter "T" is written and placed into a string. The next code is read and corresponds to "H." Now "TH" is added to the dictionary, and "H" is written and becomes the current string. Now "E" is seen, "HE" is added to the table, and "E" is written, and so on. Again, a dictionary can be used to store the codes, but a list is more efficient. The indices are codes, which are numbers, so a list is fine here. The central part of the process is as follows:

```
code1 = int(inf.readline())          # CODE1 is the first code
                                     # on the file
print (dict[code1], end="")          # Output the string for
                                     # CODE1
while True:                          # While mode codes on the
                                     # file ...
    code0 = int(inf.readline())      # CODE0 is the next code
                                     # on the file
    if code0 < len(dict):            # Is CODE0 in the table?
       s = dict[code0]               # YES. S is the string for
                                     # CODE0
    else:
```

```
        s = dict[code1]           # NO. S is the string for
                                  # CODE1
        s = s + ch                # Append CH to S.
    print (s, end="")             # IN EITHER CASE emit S
    ch = s[0]                     # CH becomes the first
                                  # character of S
    dict = dict + [dict[code1]+ch,] # Add new string to the
                                    # table
    count = count + 1
    code1 = code0
```

ON THE CD

A pseudocode summary of both the encoding and decoding processes is given in Figure 10.9, and working programs are provided on the disk (lzwe.py and lzwd.py). If punctuation is to be added, then a different conversion to uppercase would have to be done. For practical applications, the entire ASCII character set would be used at the outset.

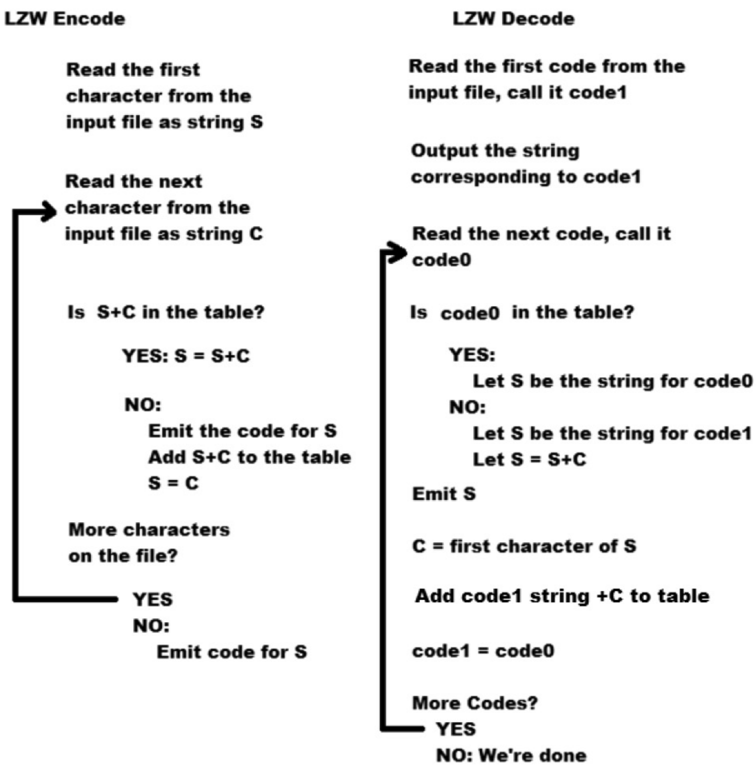

Figure 10.9
The LZW encode and decode algorithms.

10.6 HASHING

A *hashing* algorithm characterizes a complex piece of data with something simpler, and preferably unique. The most common example is to find a number that could represent a character string. A hashing algorithm has to be fast, because it often needs to convert a string into an index to a list or tuple. Consider the string “while.” There are five characters (bytes) here. How can this string be used as an index into a tuple?

Any numerical operation on the codes used to represent the character might work, but some result in codes that are too large. Simply adding the codes would give a value of 537, which could work, but also might be too large. Imagine the application is to look up Python key words; there are 33 of them. The value resulting from the hash should be an index between 0 and 32, so take the hash mod 33. If that is tried, the result is that half of the 33 entries will be empty, and half will have two or more strings that have the same index. The results are as follows:

4: “None”	12: “return”	21: “try”	31: “global”
6: “class”	13: “global”	22: “is”	
7: “from”	14: “as”	25: “finally”	
9: “while”	15: “lambda”	27: “or”	
10: “and”	17: “in”	29: “False”	
11: “continue”	20: “True”	30: “for”	

When two items hash to the same value, it is said to be a *collision*. In this case, the collisions are as follows:

(class, def)	(False, nonlocal)	(return, del)	(from, not)	(lambda, with)
(True, elif)	(while, if)	(from, yield)	(global, assert)	(False, else)
(from, import)	(and, pass)	(is, break)	(is, except)	(None, raise)

Two values cannot occupy the same location in a tuple, so something must be done. The simplest way to deal with collisions is to have extra space in the list or tuple. If the size of the tuple is specified as 145, then all strings hash to distinct values. Of course, now 112 tuple entries are empty, but does that really matter? The alternative to a table indexed by hashing (a hash table) would be a list that has to be searched, and hashing is much faster.

10.6.1 DJB2

This algorithm starts with a predefined seed for a hash value, multiplies it by 33 and adds the next character from the string, multiplies that by 33, adds the next character, and so on. The code is

```
def djb2 (s, size):
        sum = 5381
        for i in range (0, len(s)):
            sum = sum*33 + ord(s[i])
        sum = sum%size
        return sum
```

Why multiply by 33? It works well, and nobody knows why. The seed of 5381 can be changed to see how different values work. With the configuration given here, there will need to be 112 elements in the tuple to avoid collisions. If the program is changed slightly so that an exclusive OR replaces the sum, the size decreases to 105. That is

```
sum = sum*33 ^ ord(s[i])
```

10.6.2 SDBM

This is a method devised for scrambling bits, but makes for a good hashing function. The iteration is hash(i) = hash(i - 1) * 65599 + str[i]. The number 65599 is arbitrary, but it happens to be prime. A function to implement this is

```
def sdbm (s, size):
    hash = 0
    for i in range (0, len(s)):
        hash = ord(s[i]) * 65599 + hash
    return hash%size
```

There are many other hashing methods (see Knuth). The idea is an important one. It is, for example, a way to implement Python dictionaries: hash the key to an integer and use that to access the value.

10.7 SUMMARY

The goal of this chapter was to introduce important algorithms or general techniques used in computer science. Sorting is a traditional programming problem for undergraduates and is essential in many data-handling applications. The selection sort and the merge sort were discussed at length.

Searching involves finding a piece of data within a larger collection. A linear search starts at the beginning and looks at consecutive elements until the target is found. A binary search splits the data into two halves each time an element in the set is examined and so is faster, but it depends on the data being sorted.

Random number generation creates a sequence of numbers that satisfies a statistical test for randomness. Such numbers are crucial in computer simulations and games, and in some numerical algorithms.

Cryptography involves sending messages that only certain intended people can receive and understand. A cipher is an algorithm that converts one string of characters into another one of generally the same length. The one-time pad method was examined, followed by the very popular RSA algorithm.

Data compression is about ways to take many bytes of information and turn them into fewer bytes while losing none of the essential message. Of course, compressed data is incomprehensible: it must be decompressed for it to be used. This section demonstrated run length encoding, Huffman codes, and the LZW algorithm.

The final section was a brief discussion of hashing, a way to convert strings or other complex data types and reduce them to simpler forms such as integers. The djb2 and the sdbm methods were singled out as being typical of the way that such algorithms work.

Exercises

1. Hashing algorithms must be fast. Use the timing schemes discussed in this chapter to determine which of the three hashing algorithms presented is the fastest.

2. When a sequence of numbers is sorted into ascending order, then element i-1 is always smaller than or equal to element i. Here is a description of a sorting algorithm: scan the data set S to find any pairs of adjacent locations where S[i-1] > S[i], and when any are found, swap the two values. Repeat the process until the array is sorted. Does it ever get sorted? What is the best case and what is the worst case? Implement the method in Python.

3. Compare the linear congruential random number generator described in this chapter against the *random()* function in Python. Implement a die roll using

each method, and roll a die 1,000 times. Which method is nearest to the expected frequency distribution (equal for all values)? Repeat the process 1,000 times and score Python one point when its random number generator wins by this measure, and score the book's generator one point when it wins. Which is the overall winner?

4. The quality of a hashing algorithm is measured by how random the hash codes are when given a sample set of strings. One estimate of randomness is the number of cells with more than one value hashed to it (the best here would be 0), and the average number of values hashed to occupied cells—this should be close to 1. Measure these for the three hashing methods presented for a size of 60 cells.

5. Data for registrants in a swimming competition consist of the swimmer's name, number, national ranking, and time in the 200-meter freestyle competition. These data are located in four lists: **name**, **number**, **rank**, and **t200**. In all cases, the same index is used to access all of the data for the same person. Sort these data in descending order on time and identify the persons in the top three spots and their times.

6. *Steganography* works by concealing a message, rather than making it unreadable, as is done when using encryption. In the ideal situation, nobody will even suspect that there is a second message hidden within the first. Consider a scheme that uses the spaces in a message: a single space is a 0 and a double space is a 1. The letters are coded as 5-bit codes starting with A = 00000, B = 00001, and so on. Write programs that encode and decode such messages.

Notes and Other Resources

Random.org random number server: *https://www.random.org/*

A pretty good description of RSA: *https://en.wikipedia.org/wiki/RSA_%28cryptosystem%29*

Encode/decode stenographic messages disguised as spam: *http://www.spam-mimic.com/*

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CHAPTER 11

PROGRAMMING FOR THE SCIENCES

In this chapter

It is true that the earliest calculating devices were created to help with commercial concerns, like payments, credit, and inventory. The abacus is an excellent example – it does basic arithmetic and was likely an early cash register. Much older devices do exist, such as the Lebombo bone that helped ancient African bushmen do simple calculations and keep track of time. However, the electronic computer was designed to carry out scientific calculations, in particular those related to decrypting military messages and building the atom bomb. Computers are used for those things still, but there is now a vast array of computations in the scientific domain that could not be carried out without the help of a computer.

Scientists from different disciplines would disagree about what the most important algorithms and techniques for science were. That's because of the widely disparate things that they study. There are a few recurring problems that occur in almost all science domains, and some important techniques that generalize to both scientific and non-scientific areas.

11.1 FINDING ROOTS OF EQUATIONS

The root of an equation is where its value is zero. This may not be the smallest or the largest value, but the place where a function equals zero is often important. For example, if a function for the error in a calculation can be found then finding the place where the error is zero would be important. In one dimension, the problem being solved is as follows:

$$x: f(x) = 0 \tag{11.1}$$

or in other words, find the value of **x** that results in **f(x)** being equal to zero. The function could be quite complicated, but for the technique to work, it should have a derivative.

The basis of many root finding procedures is *Newton's method*. The procedure begins with a guess at the right answer. The guess in many cases does not have to be very accurate, but is simply a starting point. If a range of values is given within which to find the solution, the center of that range may be a good starting guess. Here is a problem to start with:

$$f(x) = (x-1)^3 \quad \text{between} \quad x = -2 \text{ and } x = 12 \tag{11.2}$$

the center of the range is $x = 5$.

The initial guess is called x_0, and here $x_0 = 5$. The function value there, f($x_{0)}$, is 64. The algorithm now says that the next guess for x, x_1, will be as follows:

$$x_0 - f(x_0)/f'(x_0) \tag{11.3}$$

where f'(x_0) is the derivative of **f** at the point **x=** $\mathbf{x_0}$. This is a problem: the derivative of **f** has to be calculated. A numerical method is examined a little later in this chapter, so let's code a function that gives the derivative, having done the calculus on paper and then written the function based on that. The derivative of $(x-1)^3$ is $3x^2 - 6x + 3$.

```
# Roots of a function
def objective (x):
    return (x-1)*(x-1)*(x-1)

def deriv (x):
    return 3*x*x - 6*x+3
```

```
# Range is -2 to +12
x = 5.
fx = 1000.
delta = 0.000001
print ("Step 0: x=", x, " obj = ", objective(x))
i = 1
while abs(fx) > delta:
    f = objective(x)
    ff = f/deriv(x)
    x = x - ff
    fx = objective(x)
    print ("Step ",i,": x=", x, " obj = ", fx)
    i = i + 1
```

Step 0: x= 5.0 obj = 64.0

Step 1 : x= 3.666666666666667 obj = 18.96296296296297

Step 2 : x= 2.7777777777777777 obj = 5.618655692729766

Step 3 : x= 2.185185185185185 obj = 1.6647868719199308

. . .

Step 14 : x= 1.0137019495631274 obj = 2.5724508967303e-06

Step 15 : x= 1.0091346330420865 obj = 7.622076731056633e-07

The correct answer in this case is x=1.0, so the method gets to within 0.009 of the correct root in 15 steps. Depending on the application, this could be fine. What if the initial guess was terrible? If the process starts at x = 500, then it takes 27 steps, but gets just a little closer to the right answer (x=1.0087). Starting at -500 also takes 27 steps.

It's possible that there is no root. What happens in that case? The program keeps looking. It overshoots, and then goes back, and forth, and back again. To prevent this from happening, it is common to place a limit of the number of times the program will try. When this limit is exceeded, an error occurs indicating that there is no solution.

This first example has illustrated some common concepts that are used in *numerical analysis*, which is the mathematical discipline encompassing the computation of mathematical functions and operations. The common concepts include the following:

The **initial guess**: It is relatively common to have a numerical algorithm begin at a guessed value.

The **delta**: It is also common to have an algorithm step when the change in the result or some mathematical feature becomes smaller than a specified threshold, called *delta*.

Iteration: Numerical methods frequently repeat a calculation, expecting it to converge on the correct result, using the previously calculated value as the new starting point.

Maximum iterations: A user of a numerical method can assume that the method will not converge (get close enough to the right answer) if a specified number of attempts have been made.

11.2 DIFFERENTIATION

Determining the derivative of a function is something that is often thought of as a symbolic operation, and the result is valid for any value of the function. This may not always be true, and it may not be easy to do in the general case. Think about what the previous algorithm does. It needs the derivative of a function at one specific point. Can that be determined if the algebraic form of the function is not known? Yes, it can, to within some degree of accuracy.

The derivative of a function at a point **x** is the slope of the curve defined by that function at that point. The definition of the derivative of **f** at the point **x** is as follows:

$$f'(x) = (f(x+h) - f(x-h))/(2h) \tag{11.4}$$

h gets smaller and smaller, reaching what is called a *limit* in calculus. This formula is essentially the mathematical definition of a derivative. On a computer, **h** can be made quite small, but can never be zero. If the expression above is used as an estimate of the derivative it will work in many cases. It is based on sampling two points of the function each time. An improvement can be made by using more points. For example,

$$f(x) = \frac{-f(x+2h) + 8f(x+h) - 8f(x-h) + f(x-2h)}{12h} \tag{11.5}$$

uses four points and often produces better results.

Coding this uses a function passed as a parameter. It makes sense that the function to be differentiated would be a parameter to the function that differentiates it; other parameters will be **x**, the point at which it will be evaluated, **delta**, the accuracy desired, and **niter**, the maximum number of iterations. The calculation should take place in a try-except block so that numerical errors will be caught. The two-point and the four-point versions of the function that performs numerical differentiation are as follows:

```
def deriv1 (f, x, delta=0.0001,
niter=20):   # Two point
             # derivative
    global n0
    h = 0.001
    n = 0
    dx = f(x)
    while n<niter:
        try:
            old_dx = dx
          dx = (f(x+h)-f(x-h))/
                              (2*h)
            n = n + 1
            if abs(dx-old_dx) <
                             delta:
                n0 = n
                return dx
        except:
            print ("Exception
                   deriv1")
            return 0
```

```
def deriv2 (f, x, delta=0.0001,
niter=20):   # Four point
             # derivative
    global n1
    h = 0.001
    n = 0
    dx = f(x)
    while n<20:
        try:
            old_dx = dx
            dx =(-f(x+2*h)+
                     8*f(x+h)- \
             8*f(x-h)+
                  f(x-2*h))/(12*h)
            n = n + 1
            if abs(dx-old_dx) <
                             delta:
                n1 = n
                return dx
        except:
            print ("Exception
                   deriv2")
            return 0
```

Testing these functions is an excellent demonstration. First, a function to be differentiated is written. The previous example on finding roots has a simple one (renamed as f1):

```
def f1 (x):
    return (x-1)*(x-1)*(x-1)
```

That example also has a function that represents the derivative of f1 at the point **x** (renamed df1):

```
def df1 (x):
    return 3*x*x - 6*x+3
```

The function **df1()** should return the exact derivative of **f1()**, and can be used to check the value returned by **deriv1()** or **deriv2()**. Create a loop that runs over a range of **x** values and compare the value returned from **df1()** to that returned by **derive1()** and/or **deriv2()**:

```
for i in range (1,20):
    x = i*1.0
    f = f1(x)
    df = df1(x)
    mydf = deriv1 (f1, x)
    mydf2 = deriv2(f1, x)
    print (f, df, mydf, n0, "   ", mydf2, n1)
```

The result looks something like this:

f(x)	df(x)	result from deriv1	Niter	result from derive2	Niter
0.0	0.0	9.999999e-07	1	-2.2209799e-19	1
1.0	3.0	3.0000009999	2	2.999999999999	2
8.0	12.0	12.00000099999	2	11.999999999999	2
		.	.	.	
4913.0	867.0	867.0000010015	2	867.0000000024	2
5832.0	972.0	972.000001001	2	972.0000000021	2

Both functions give excellent results in a very few iterations in this case. Of course, some functions present more difficulties than do simple polynomials (See Press et al. in the References).

11.3 INTEGRATION

An integral is most often thought of as the *area under a curve*, where the curve is a function (Figure 11.1a). Numerical integration amounts calculating that area using an algorithm. The area of a rectangle is easy to calculate, so if the region under a curve could be reasonably approximated by a bunch of rectangles, then the problem would be solved. This is the idea behind the *trapezoidal rule*. The integral from x0 to x1 of a function f(x) can be approximated by the width (x1-x0) multiplied by the height (the average value of the function in that range), which is just a rectangle that approximates the area under the curve (Figure 11.1b). In mathematical notation, this is

$$\int_{x0}^{x1} f(x) = (x_1 - x_0)\frac{(f(x_0) + f(x_1))}{2} \tag{11.6}$$

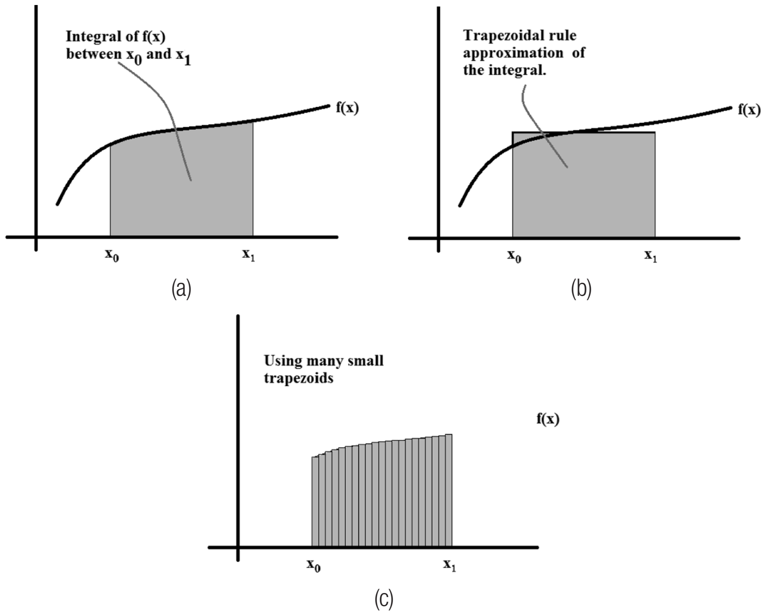


Figure 11.1
Numerical integration by summing many small areas under a curve.

This would generally be a pretty poor approximation of a curve, and would yield correspondingly bad approximations of the integral. However, the smaller the width x_1-x_0, the more accurate the approximation can be, and so using a great many small trapezoids would be much better than using only one (Figure 11.1c). How many? That is not known at the outset, but could be increased from an initial guess until a desired accuracy was achieved.

A function that performs integration using this method would accept a function, the starting $\mathbf{x_0}$ and the ending $\mathbf{x_1}$ for the integral. The function would break the interval between $\mathbf{x_0}$ and $\mathbf{x_1}$ into **n** parts, when **n** is an initial guess. The function is evaluated for all **n** parts, the area of each trapezoid is computed, and they are summed to get the final result. Now increase **n** and do it again. If the two values are close enough (**delta**), then the process is complete.

This is done in two steps, first using a function **trap0()** that computes and returns the sum of N trapezoids. The obvious but slow way to do this is shown in the following code.

```
def trap0 (f, x0, x1, n):   # Slow method
```

```
    dx = (x1-x0)/n           # Divide range into N parts
    xa = x0                  # Start at x0
    xb = x0+dx               # Current trapezoid is xa to xb
    sum = 0                  # Sum of areas starts at 0.0
    for i in range(0, n):    # Add up N trapezoids
        f0 = f(xa)           # Compute function at xa and xb
        f1 = f(xb)
        sum = sum + dx*(f1+f0)/2  # Area of the trapezoid
        xa = xa + dx         # Next xa and xb are dx from
        xb = xb + dx         # the current ones
    return sum               # The sum is the integral.
```

The integration function **trapezoid()** calls this function with increasing values of **n** until two consecutive results show a small enough difference (i.e., it is smaller than a provided delta value):

```
def trapezoid (f, x0, x1, delta=0.0001, niter=1024):
    n = 4
    resold = trap0(f, x0, x1, 2)
    resnew = trap0(f, x0, x1, 4)
    while abs(resnew-resold) > delta:
        if n>niter: break
        resold = resnew
        n = n * 2
        resnew = trap0 (f, x0, x1, n)
    return resnew
```

The function **trap0()** can be sped up significantly by not re-computing the function twice each time through the loop, but remembering the previous value instead (Exercise 2). A more popular algorithm for integration is *Simpson's Rule*, which tries to minimize the error even more by using a quadratic approximation to the curve at the top of the trapezoid, instead of a straight line.

11.4 OPTIMIZATION: FINDING MAXIMA AND MINIMA

Finding extreme values, either the maximum or minimum, is a very common problem in computing, not just in science but in many disciplines. It is sometimes referred to as optimization. Naturally finding a *best* (in some sense) value would be appealing. What is the least amount of fuel needed to travel from Chicago to Atlanta? What route between those two cities requires the least amount of driving time? What route is shortest in terms of distance? There are many reasons to want an optimum and many ways to define what an optimum is.

In the following discussion, the function to be optimized is provided. The problem is how to find the location (parameters) where the minimum or maximum occurs.

11.4.1 Newton Again

Figure 11.2 shows an example of a function to be maximized. There is a maximum of zz at the point x= x. How can this be found? If the nature of the function is known, for instance that it is a quadratic polynomial, then the optimum can be found immediately. It will be at the point where the derivative is zero. The problem of optimization is that one does not know much, if anything, about the function. It can only be evaluated, and perhaps the derivatives can be found numerically. Given that, how can the min or max be found?

If the derivative can be found, then it may be possible to search for an optimum point. At a value **x**, if the derivative is negative, then the slope of the curve is negative at that point; if the derivative is positive, then the slope is positive. If an x value can be found where the slope is negative (call this point $\mathbf{x_0}$) and another where it is positive (call this $\mathbf{x_1}$), then the optimum (slope = 0) must be between these two points. Finding that point can be done as follows:

1. Select the point between these two (x = ($\mathbf{x_0}$+ $\mathbf{x_1}$)/2).
2. If the derivative is negative at this point, let $\mathbf{x_0}$ = x. If positive, let $\mathbf{x_1}$ = x.
3. Repeat from Step 1 until the derivative is close enough to 0.

This process is almost random. Finding the two starting points is a matter of guessing until they are found. The search range gets smaller by a factor of 2 each iteration. The fact that the function can be evaluated at any point means that it is possible to make better guesses. In particular, it's possible to assume that the function is approximately quadratic at each step. Quadratics have an optimum at a predictable place. The method called *Newton's Method* fits a quadratic at each point and moves towards its optimal point.

The method is iterative, and without doing the math, the iteration is

$$x_n = x_{n-1} - \frac{f'(x)}{f''(x)} \qquad (11.7)$$

A function to calculate the first and second derivative is needed. The formula for the second derivative is based on the definition of differentiation, as was the formula for the first. It is

$$f''(x) = \frac{f(x+h) - 2f(x) + f(x-h)}{h^2} \tag{11.8}$$

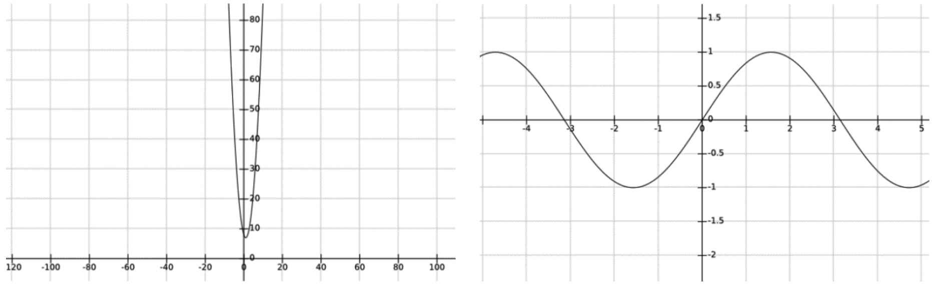
The program should be straightforward. Repeat the calculation of $x_{n-1} - f'(x)/f''(\mathrm{x})$ until it converges to the answer. This will be the location of the optimum. An example function is as follows:

```
def newtonopt (f, x0, x1, delta=0.0001, niter=20):
    x = (x0+x1)/2
    fa = 1000.0
    fb = f(x)
    i = 0
    print ("Iteration 0: x=", x, " f=", fb)
    while (abs(fa-fb) > delta):
        fa = fb
        x = x - deriv(f, x)/derivsecond(f, x)
        fb = f(x)
        i = i + 1
        print ("Iteration ", i, ": x=", x, " f=", fb)
        if i>niter:
            return 0
```

This finds a local optimum between the values of x0 and x1. A local optimum may not be the largest or smallest function value that the function can produce, but may be the optimum in a local range of values.

Figure 11.2a shows a typical quadratic function. It is $f(x) = x^2 - 2x + 8$, and has an optimum at x=1. Because it is quadratic, the Newton optimization function above finds the result in a single step. Figure 11.2b is a sine function, and can be seen to have many minima and maxima. Any one of them might be found by the Newton method, which is why a range of values is provided to the function.

The **newtonopt()** function successfully finds the optimum in Figure 11.2a at $x = 1$, and finds one in Figure 11.2b at $x = 90$ degrees (p/2 radians). If there is no optimum the iteration limit will be reached. If either derivative does not exist, then an exception occurs.



(a) (b)

Figure 11.2
(a) Analytical function with a minimum. (b) A sine function has many minima and maxima.

11.4.2 Fitting Data to Curves – Regression

Scientists collect data on nearly everything. Data are really numerical values that represent some process, whether it be physical, chemical, biological, or sociological. The numbers are measurements, and scientists model processes using these measurements to further understand them. One of the first things that is usually done is to try to find a pattern in the data that may give some insight into the underlying process, or at least allow predictions for situations not measured. One of the common methods in data analysis is to *fit a curve* to the data; that is, to determine whether a strong mathematical relationship exists between the measurements.

As an example, a set of measurements of tree heights will be used. The height of a set of a specific variety of trees is made over a period of ten years, and the data resides in a file named "treedata.txt." Is there a linear relationship (i.e., does a tree grow generally the same amount each year)? Specifically, what is that relationship (i.e., how much can we expect a tree to grow)? Figure 11.3 shows a visualization of these data in the form of a *scattergram* or *scatter plot*, in which the data are displayed as points in their (x,y) position on a grid.

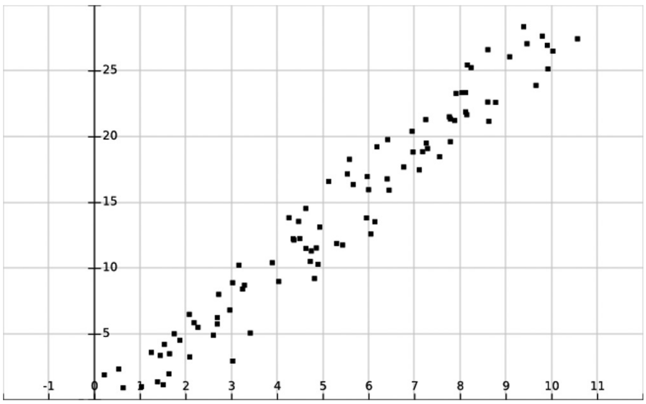


Figure 11.3
A scattergram of a typical set of measurements.

The "curve" to be fit in this case is a line. What is the equation of the line that best represents the data in the Figure? If that were known, then it would be possible to predict the height of a tree with some degree of confidence or to estimate a tree's age from its height.

One form of the equation of a line is the point-slope form:

$$y = mx + b$$

where **m** is the *slope* (angle) of the line and **b** is the *intercept*, the place where the line crosses the Y axis. The goal of the *regression* process, in which the best line is found, is to identify the values of **m** and **b**. A simple observation is needed first. The equation of a line can be written as

$$\mathbf{mx + b - y = 0} \tag{11.9}$$

If a point actually sits on this line, then plugging its **x** and **y** values into the equation results in a 0 value. If a point is not on the line, then **mx + b - y** results in a number that amounts to an error; its magnitude indicates how far away the point is from the line. Fitting a line to the data can be expressed as an optimization problem: find a line that minimizes the total error over all sample data points. If $(\mathbf{x_i}, \mathbf{y_i})$ is data point **I**, then the goal is to minimize

$$\sum_{i=0}^{n}(mx_i + b - y_i)^2 \tag{11.10}$$

by finding the best values of **m** and **b**. The expression is squared so that it will always be positive, which simplifies the math. It may be possible to do this optimization using a general optimization process such as Newton's, but fortunately, the math has been done in advance for a straight line. Other situations are more complicated, depending on the function being fit and the number of dimensions

A simple linear regression is done by looking at the data and calculating the following:

meanX = mean value of $x = \frac{\sum x}{n}$

MeanY = mean value of $y = \frac{\sum y}{n}$

stdX = standard deviation of $x = \sqrt{\frac{\sum (x - \text{mean}x)^2}{n-1}}$

stdY = standard deviation of $y = \sqrt{\frac{\sum (y - \text{mean}y^2)}{n-1}}$

r = correlation between *x* and $y = \frac{\sum (x - \text{mean}x)(y - \text{mean}y)}{\sqrt{\sum x^2 \sum y^2}}$

Each of these can be calculated using a separate function. Then the slope of the best line through the data would be:

$$m = r\frac{\text{std}y}{\text{std}x} \tag{11.11}$$

And the intercept is:

$$\text{b} = \text{meany} - \text{m*meanx} \tag{11.12}$$

The function **regress()** that does the regression accepts a tuple of X values and a corresponding tuple of Y values, and returns a tuple **(m, b)** containing the parameters of the line that fits the data. It depends on other functions to calculate the mean, standard deviation, and correlation; these functions could generally be more useful in other applications. The entire collection of code is:

```
from math import *

def mean (x):
    sum = 0.0
   for i in range (0, len(x)):
        sum = sum + x[i]
    sum = sum/len(x)
    return sum

def sdev (x, meanx):
    sum = 0
    for i in range(0,len(x)):
        sum = sum +
              (x[i]-meanx)*
               (x[i]-meanx)
    sum = sum/(len(x)-1)
    return sqrt (sum)

def correlate (x, y, meanx,
               meany):
    sum1 = 0
    sumx2 = 0
    sumy2 = 0
    for i in range(0,len(x)):
        z = (x[i]-meanx)*
                (y[i]-meany)
        sum1 = sum1 + z
        sumx2 = sumx2 + \
           (x[i]-meanx)*
                (x[i]-meanx)
        sumy2 = sumy2 + \
           (y[i]-meany)*
                (y[i]-meany)
    return sum1/
           sqrt(sumx2*sumy2)
```

```
def regress (x, y):
    mx = mean(xdata)
    my = mean(ydata)
    sdx = sdev (xdata, mx)
    sdy = sdev (ydata, my)
    if sdx == 0: return
    r = correlate
         (xdata,ydata,mx,my)
    m = r * sdy/sdx
    b = my - m * mx
    return (m, b)

f = open ("treedata.txt",
                        "r")
s = f.readline ()
xdata = ()
ydata = ()

# Main program: test regress
# Read each lines as a string
# and split at the comma;
# 2 reals
while s != "":
   for i in range (1,len(s)):
       if s[i] == ",": break
    x = float(s[0:i-1])
    y = float(s[i+1:])
    xdata = xdata + (x,)
    ydata = ydata + (y,)
    s = f.readline()

line = regress(x, y)
```

11.4.3 Evolutionary Methods

A *genetic algorithm* (GA) or an *evolutionary algorithm* (EA) is an optimization technique that uses natural selection as a metaphor to optimize a function or process. The idea is to create a collection of many possible solutions (a *population*), which are really just sets of parameters to the objective function. These are evaluated (by calling the function) and the best of them are kept in the population; the remainder are discarded. The population is refilled by combining the remaining parameter sets with each other in various ways in a process that mimics reproduction, and then this new population is evaluated and the process repeats.

The population contains the best solutions that have been seen so far, and by recombining them, a new, better set of solutions can be created, just as nature selects plants and animals to suit their environment. This method does not require the calculation of a derivative, so it can be used to optimize functions that cannot be handled in other ways. It can also deal with large dimensions, that is, functions that take a large number of parameters.

Consider the problem of finding the minimum of a function of two variables. This is an attempt to find values for x and y that result in the smallest function result. Evolutionary algorithms are often tested on difficult functions with numerous local minima or large flat regions. Two such functions are used here: the *Goldstein-Price* function,

$$(1 + (x + y + 1)^2 (19 - 14x + 3x^2 - 14y + 6xy + 3y^2) \\ (30 + (2x + 3y)^2 (18 - 32x + 12x^2 + 48y - 36xy + 27y^2)) \quad (11.13)$$

and *Bohachevsky's* function,

$$x^2 + y^2 - 0.3 \cos(3\pi x) - 0.4 \cos(4\pi y) + 0.7 \quad (11.14)$$

Graphs of these functions are shown in Figure 11.4.

The first step in the evolutionary algorithm is to create a population of potential solutions. This is a collection of parameter pairs **(x,y)** created at random. The population size for this example is 100, and is a parameter of the EA process. This is done in the following way:

```
def genpop (population_size):
    pop = ()
    for i in range(0, population_size):
        p = (randrange(-10, 10),  randrange(-100, 100))
        pop = pop + (p,)
    return pop
```

The population is a tuple of a hundred **(x, y)** parameter pairs. These need to be evaluated, and so the objective function must be written. This differs for each

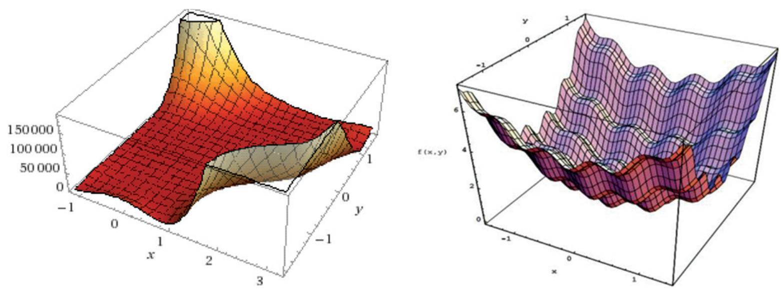


Figure11.4
Two dimensional functions to be optimized.

optimization problem. In this case, it is the sum of the errors between a given line (one of the parameters) and the data points. One way to calculate this is:

```
def objective (x, y):         # One of many possiblke
                              # objective functions
    return goldsteinprice (x, y)
#   return boha (x, y)

def goldsteinprice (x, y):   # Goldstein-Price function
                             # f(0, -1) = 3
    return (1+(x+y+1)**2 * (19-14*x+3*x*x - 14*y +6*x*y +
                             3*y*y)) * \ (30+(2*x-3*y)**2 *
                        (18-32*x+12*x*x+48*y-36*x*y+27*y*y))

def boha (x, y):
    z = x*x + y*y -0.3*cos(3*pi*x) - 0.4*cos(4*pi*y) + 0.7
    return z
```

All members of the population are evaluated, and the best ones (in this case, the ones with the smallest objective function value) are kept. A good way to do this is to have the values in a tuple **E**, where **E[i]** is the result of evaluating parameters **P[i]**, and sorting the collection is the descending order on **E**. Since there are 100 entries in **E**, this means that **E[0:n]** contains the best **n%** of the population. The function **eval()**creates a tuple of the function evaluations for the whole population, and **sort()** organizes these and the corresponding parameters. These contain nothing new, and are not be shown here. The program here selects the best 10% and discards the remainder, replacing them with copies of the good ones.

The key issue is one of introducing variety in the population. This means changing the values of the parameters while, one would hope, improving the overall performance of the group. Using the metaphor of natural selection and genetics, there are two ways to introduce change into the population: mutation and crossover. *Mutation* involves making a small change in a parameter. In real DNA, a mutation changes one of the base pairs in the sequence which would usually amount to a rather small change, but which would be fatal in some cases. In the EA we are writing, a mutation is a random amount added to or subtracted from a parameter. Mutations occur randomly and with a small probability, which is named **pmut** in the program. Values between 0.015 and 0.2 are typical for **pmut**, but the best value cannot be determined, and it is problem specific. A value of 0.02 is used here.

The function **mutate()** examines all elements in the global population, mutating them at random (i.e., adding random values).

```
def mutate (m):
    global pmut, population
    for i in range (int(m), len(population)):
        c = population[i]
        if random () < pmut:         # Mutate the x parameter
            c[0] = c[0] + random()*10.0-5
        if random () < pmut:         # Mutate the y parameter
            c[1] = c[1] + random()*10.0-5
        population[i] = c
```

A crossover is more complex, involving two sets of parameters. It involves swapping parts of the parameters sets from two "parents." Some parameters could be swapped entirely, in this case meaning that (x0, y0) and (x1, y1) become (x0, y1) and (x1, y0). Other times, parts of one parameter would be combined with parts of another. There are implementations involving bit strings that make this easier, but when using floating point values as is being done here, a good way to do a crossover is to select two parents and replace one of the parameters in each with a random value that lies between the original two.

```
def crossover (m):
    global population, pcross
    for i in range (m, len(population)):  # Keep the best
                                           # ones unchanged
        if random () < pcross:             # Crossover at
                                           # the given rate
            k = randrange(m, len(population)) # Pick a
                                               # random mate
            w = randrange (0, 1)          # Change X or Y?
            c = population[i]             # Get individual 1
```

```
g1 = c[w]                      # Get X or Y for
                               # this guy
cc = population[k]             # get individual 2
g2 = cc[w]                     # Get X or Y
if (g1>g2): t = g1; g1 = g2; g2 = t
                          # swap so g1 is smallest
c[w] = random()*(g2-g1) + g1   # Generate new
                               # parameter for 1
cc[w] =random()*(g2-g1) + g1   # Generate new
                               # parameter for 2
```

Sample output from three attempts to find the optimal value of Bohachevsky's function is as follows:

Iterations	x	y	Result
5	[0.002528698,	0.0]	at 9.158793881192118e-05
173	[5.38185770e-10,	-0.0006229]	at 1.2643415301605287e-05
4	[-0.0007491,	0.0]	at 8.0394329584621e-06

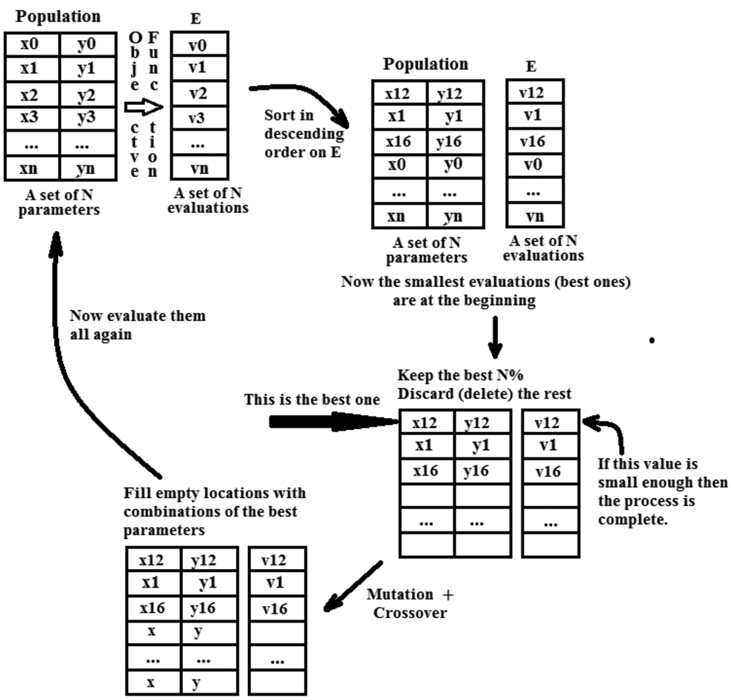


Figure 11.5
The evolutionary algorithm process.

These results show that sometimes the process takes much more time to arrive at a solution than others. It depends on the initial population, as well as on the parameters of the program: the mutation and crossover probabilities, the percentage of the top individuals to retain, and the nature of the mutation and crossover operators themselves.

Figure 11.5 outlines the overall process involved in the optimization. Details on specific techniques can be found in the references.

11.5 LONGEST COMMON SUBSEQUENCE (EDIT DISTANCE)

So far in this chapter, the methods being discussed are numerical ones. There are, however, many algorithms that are not numeric in nature, but are more symbolic, involving patterns, pictures, sounds, or other more complex data forms. It is true that at some level all problems to be solved on a computer must be formulated using numbers, but in the examples so far, the numbers are the subject of the problem, and the problem would be solved numerically even if done with a pencil and paper. In other cases, this is not so.

As a major example, consider the problem of comparing two sequences of DNA. A sequence in this instance consists of a string of letters, each one referred to as a *base* in the sequence. DNA consists of a long sequence of base pairs involving four molecules: Adenine (A), Guanine (G), Thymine (T), and Cytosine (C), linked together chemically. These ultimately define the structure of a protein, and it is the sequence that is important. A common problem in computational biology is to find the longest sequence in common between two DNA strands, where the samples may be from different individuals or even different species. Methods for doing this tend to involve the edit distance or Levenshtein distance.

The *edit distance* is a way of specifying how similar or dissimilar two strings are to one another by finding the minimum number of editing operations required to transform one string into the other. An editing operation can be a change in a character, a deletion, or an insertion. For example, what is the edit distance between the word "planning" and the word "pruning"? It is 3:

p l a n n i n g	
p **r** a n n i n g	change "l" to "r"
p r **u** n n i n g	change "a" to "u"
p r u n i n g	delete "n"

How is this used when looking at DNA? A DNA sequence is a set of the codes read from a piece of DNA, and it is a string containing only the letters G,A,T, and C. Comparing two pieces of DNA is a matter of comparing the two strings. The two strings AGGACAT and ATTACGAT are distance 3 from each other. The longest common sub-sequence has 5 characters in it:

```
AGGAC AT
ATTACGAT
```

11.5.1 Determining Longest Common Subsequence (LCS)

Exhaustive searching the two strings S1 and S2 for the longest common sub-sequence is simply be too slow for any practical purpose. Fortunately, we now have the *Smith-Waterman* method. It builds a matrix (two-dimensional array) where each character of the first string represents a column of the matrix, and each character in the other string forms a row, in order of appearance. The matrix is filled with numbers using the following relation:

$$T(i,j) = \max \begin{bmatrix} T(i-1,j-1) + \sigma(S_1(i), S_2(j)) \\ T(i-1,j) + \text{gap penalty} \\ T(i,j-1) + \text{gap penalty} \\ 0 \end{bmatrix} \tag{11.15}$$

The function σ**(a,b)** gives a penalty for a match/mismatch between two characters a and b. Here, it is 2 for a match and -2 for a miss. The *gap penalty* is the value assigned to leaving a gap in the sequence to perform a better match. Usually, this is -1. The scheme offers a degree of flexibility, so that different penalties (and rewards) can be applied in different circumstances.

The first step in the Smith-Waterman method is to create a matrix (a table) **T** in which there are **len(S1+1)** columns and **len(S2+1)** rows. The first index in T(i,j) refers to the column, and the second index is the row. The values in the current row are a function of those in the previous one. Place a 0 in each element of the first row and the first column. For the two strings used previously, this would look like Table 11.1.

Table 11.1
First step in the Smith-Waterman method

S2 \ S1		A	G	G	A	C	A	T
	0	0	0	0	0	0	0	0
A	0	*						
T	0							
T	0							
A	0							
C	0							
G	0							
A	0							
T	0							

Now, for any element T(i,j) the neighboring elements are as follows:

$T(i-1, j-1)$ $T(i, j-1)$ $T(i+1, j-1)$
$T(i-1, j)$ $T(i, j)$ $T(i+1, j)$

The first cell to fill in the table T is T(1,1), marked with a * character in Table 11.1. The relation used to fill this cell has four parts:

1. $T\left(i-1, j-1\right) + \sigma(S_1(i), S_2(j))$
   The characters in the row and column match, so $\sigma\left(S_1(i), S_2(j)\right) = \sigma(A, A) = 1 + T(0,0) = 2$
2. Gap penalty is -1, $T(i\ \text{-}1, j) = 0$, $T(0,1) = 0$. Result is -1
3. Gap penalty is -1, $T(i, j\text{-}1) = T(1, 1) = 0$. Result is -1
4. Result is 0

The maximum value of these four calculations is 1, so $T(1, 1) = 2$.

Table 11.2
The next step in the Smith-Waterman method

S2 \ S1		A	G	G	A	C	A	T
	0	0	0		0	0	0	0
A	0	2	*					
T	0							
T	0							
A	0							
C	0							
G	0							
A	0							
T	0							

The next cell to compute is T(2,1). This time, the two characters are not the same, so

1. $T(i-1, j-1) + \sigma(S_1(i), S_2(j))$ where $\sigma(S_1(i), S_2(j)) = \sigma(G, A) =$ -1 + $T(1, 0) = -2$
2. Gap penalty is –1, $T(i–1, j) = T(1, 1) = 2$.

   Result is 2 – 1 = 1
3. Gap penalty is –1, $T(i, j-1) = T(2, 1) = 0$. Result is –1
4. Result is 0

   and so $T(2, 1) = 1$

For $T(3, 1)$,

1. G and A are not the same, $\sigma(G,T) = –2$:
2. $T(i–1.j) = T(2,1) = 1$ so 1–1 = 0
3. $T(i, j–1) = T(3,0) = 0$ so 0 – 1 = –1
4. 0

   Result is 0

For $T(4, 1)$,

1. $\sigma(A, A) = 2$,
2. $T(i–1, j) = T(3, 1) = 0$, 0-gap = –1
3. $T(i, j–1) = T(4, 0) =0$, 0-gap = –1
4. 0

   Result is 2

For T(5,1),

1. $\sigma(C, A) = –2$,
2. $T(i–1, j) = T(4, 1) = 2$, 2-gap = 1
3. $T(i, j-1) = T(5, 0) =0$, 0-gap = –1
4. 0

   Result is 1</NL>

For $T(6,1)$,

1. $\sigma(A, A) = 2$,
2. $T(i–1, j) = T(5, 1) = 1$, 1-gap = 0

3. $T(i, j{-}1) = T(6\ 0)$ =0, 0-gap = –1
4. 0

   Result is 2

Finally for T(7,1),

1. $\sigma(T, A)$ = -2,
2. T(i–1,j) = T(6, 1) = 2, 2-gap = 1
3. $T(i, j{-}1) = T(7\ 0)$ =0, 0-gap = –1
4. 0

   Result is 1

The result after row 2 is complete is shown in Table 11.3.

Table 11.3
Results after row 2 is completed

S2 \ S1		A	G	G	A	C	A	T
	0	0	0	0	0	0	0	0
A	0	2	1	0	2	1	2	1
T	0							
T	0							

Now, move to the next row. The process repeats until all cells have been examined and assigned values. For this example, the final matrix is shown in Table 11.4.

Table 11.4
Final matrix result using the Smith-Waterman method

S2 \ S1		A	G	G	A	C	A	T
	0	0	0	0	0	0	0	0
A	0	2	1	0	2	1	2	1
T	0	1	0	0	1	0	1	4
T	0	0	0	0	0	0	0	3
A	0	2	1	0	2	1	2	2
C	0	0	1	0	0	4	3	2
G	0	0	3	2	1	3	2	1
A	0	2	2	1	4	3	5	4
T	0	1	1	0	3	2	4	7

The lower right entry is column 7, row 8, or (7,8).

This matrix indicates the degree of match at points in the string. To determine the actual match between the strings, begin with the largest value in the matrix.

In this case, it is in the lower right corner, but that's not always true. Wherever the maximum is, start at that point in the matrix and trace left and upwards; this is essentially moving from the end of each string back to the beginning. At each step the move is left, up, or diagonally.

The process builds two ways to match the string. One indicates how to change **s1** into **s2** (call this **M1**), and the other indicates how to turn **s2** into **s1** (call this **M2**). Both strings are constructed from, in this case, (7,9) back to (0,0).

```
def backtrack():
    global s1, s2
    mi = 0
    mj = 0
    m1 = ""
    m2 = ""
    maxv = T[mi][mj]
    for j in range (1, len(s2)+1):
       for i in range
                 (1, len(s1)+1):
           if T[i][j] >= maxv:
               maxv = T[i][j]
               mi = i
               mj = j
```

This backtracking stage is challenging. Begin with two empty strings, **M1** and **M2**. Locate the largest value in the matrix (there may be more than one) and begin at that set of i,j coordinates: call this point **(mi,mj)**

```
while mi>0 or mj>0:
  t11 = T[mi-1][mj-1]   # Diagonal
  t01 = T[mi][mj-1]     # Up
  t10 = T[mi-1][mj]     # Left
```

A step to the left from this point is to **(mi-1, mj)**; upwards is **(mi, mj-1)**; diagonally up-left is **(mi-1,mj-1)**. The direction to be selected is the one that has the largest value of **T**, with a bias towards the diagonal if there is no specific maximum (i.e., all three are equal).

```
# Diagonal is best
  if t11>=t01 and t11 >= t10:
    m1 = s1[mi-1] + m1
    m2 = s2[mj-1] + m2
    mi = mi - 1
    mj = mj - 1
```

A movement in the diagonal direction implies a simple match or mismatch. The action should be to copy the corresponding character from **s1** into **M1** and the character from **s2** into **M2**, then set **mi = mi – 1** and **mj = mj – 1**.

<table>
<tr><td><pre># UP is best
  elif t01>t11 and t01 > t10:
      m1 = s1[mi-1] + m1
      m2 = "_" + m2
      mj = mj - 1</pre></td><td>A movement upwards implies that there is to be a gap inserted into M2, and so s1 matches. Place a "_" character into M2 and place the current (mi) character into M1. Leave mi alone but let mj = mj – 1, thus moving up in the matrix.</td></tr>
<tr><td><pre># Left is best
  elif t10>t11 and t10>t01:
      m1 = "_"+m1
      m2 = s2[mj-1]+m
      mi = mi - 1</pre></td><td>A movement left implies that a gap is to be inserted into M1, and so M2 matches. Place a "_" character into M1 and s1[mj] into M2. Leave mj alone, but set mi = mi – 1, thus moving left.</td></tr>
<tr><td><pre># End of WHILE Loop</pre></td><td>This process continues until either mi or mj becomes smaller than 0.</td></tr>
<tr><td><pre>if mi>0:
    m1 = s1[0:mi] + m1
if mj > 0:
    m2 = s2[0:mj] + m2</pre></td><td>If mi or mj is not zero, it means there are some characters left over in one of the two strings. Copy them into the corresponding match string M1 or M2.</td></tr>
</table>

If there is more than one cell in T with a maximum value, then a route should be traced back from each maximum.

For the example string, the result is

M1 = `AGGACCAT`

M2 = `ATTAC_AT`

There is a mismatch at the GG/TT pair and an inserted gap in M2.

11.5.2 NumPy

Let us now discuss the numerical Python package, NumPy. Python executes slowly by standards of languages like C and Julia because it is interpreted, not compiled into machine code. It also provides high level data structures like lists and dictionaries, and these involve a certain amount of computational overhead (they can be slow).

NumPy tries to get past this by using a new data structure that has much less overhead than does a list: the ndarray. It is a homogeneous (all elements have the same type) multi-dimensional (vectors, matrices, and more) table of the same kind as a C or Java array. An ndarray is indexed by unsigned integers beginning at 0. NumPy offers other features, but let's start here.

11.5.3 One Dimensional Arrays (Vectors)

A one-dimensional array is usually used to represent a mathematical *vector* in scientific programming. A common use of a vector is to represent a direction. Let's have an object at a location P = (x,y) on the screen, and give it a velocity of 4.5 in the x direction and 3 in the y direction. The velocity vector is V = (4.5, 3) as a tuple. Each iteration, the object will move by this amount, so in the first iteration x = x + 4.5 and y = y+3 will give the new position of the object. As vectors, we say that P = P + V.

There are four ways to create a vector like this in NumPy. First, we can use the built-in function **array** and pass it the tuple or list:

```
V = array((4.5, 3))              # from numpy import *
```

or

```
V = numpy.array((4.5, 3))       # import numpy
```

depending on how NumPy was imported. The variable **V** is now a NumPy array. Another way to create an array is by using the **arange** function:

```
V = arange(start, end, inc)
```

This initializes the array as numbers from **start** to **end** in increments of **inc**. The statement

```
V = arange(0, 10, 1)
```

gives **V** the value [0 1 2 3 4 5 6 7 8 9]. Starting at value 0 for 10 values, add 1 each time. A vector of length 2 could be created for V and then the values we want could be assigned:

```
V = arange(1., 2., 1)
V[0] = 4.5
V[1] = 3
```

Unlike other parts of Python, NumPy pays some attention to types. Notice that the call to **arange** use floating point numbers as start and end values. This creates a floating point *nparray*. If the statement had been **V = arange(1, 2, 1)** then the array **V** would contain integers.

The **linspace** function also creates an array, and is used when floating point arguments are used as parameters. It can be difficult to predict how the **arange** function will work sometimes. How many elements are created by the call **arange**(1,3,0.3)? The answer is 7:

```
[1.  1.3  1.6  1.9  2.2  2.5  2.8]
```

What **linspace** does is divide a range equally into N parts. So

```
linspace(1, 3, 9)
```

divides the range between 2 and 3 into 9 divisions:

```
[1.   1.25 1.5  1.75 2.   2.25 2.5  2.75 3.  ]
```

Finally, an array full of zeros is created:

```
z = zeros((3))
```

This creates an 1D array with 3 zero values:

```
[0. 0. 0.]
```

We can do basic arithmetic on arrays. If V = array((4.0, 3.0)) and W = array((5.0, 7.0)) then,

```
V+W is [ 9. 10.]
V-W = [-1. -4.]
V*W = [20. 21.]
V/W = [0.8    0.42857143]
```

We can do arithmetic with simple numbers (scalars), too:

```
2*W = [10. 14.]
```

The vector dot product is

```
V.dot(W) = 41.0.
```

Relational operators can be applied. So,

```
V<W = [ True  True]
```

We can apply NumPy mathematics functions (not standard math library ones):

```
log(W) = [1.60943791 1.94591015]
```

The power of this new type is better illustrated in two dimensions as matrix operations.

11.5.4 Two Dimensional Arrays (Matrices)

Creating a matrix is done by passing the **array** function a list of lists, one for each row of the matrix. Consider the 3x3 matrix,

```
A = array( [[1, 0, 2], [0, 1, 1] [0, 2, 1] )
```

which is written in mathematical form as

$$\begin{bmatrix} 1 & 0 & 3 \\ 0 & 1 & 1 \\ 0 & 2 & 1 \end{bmatrix} \tag{11.16}$$

All of the operators that have been described so far apply to these too, but also matrix multiplication. Multiplying A*A is simply done by using the @ operator:

```
A@A = [[1 4 4]
               [0 3 2]
               [0 4 3]]
```

Another convenient aspect of *nparray* is *upcasting*, meaning that the type of the array can change depending on the type of the operands. Multiplying an integer array by a floating point one gives a floating-point result.

Want a matrix of random numbers? First we create an instance of the NumPy random number generator, because the usual one does not know about NumPy types:

```
r = random.default_rng(1)
```

Now, call **random** with the size of the matrix:

```
x = r.random((3,3))
```

which gives the result

```
[[0.51182162 0.9504637  0.14415961]
[0.94864945 0.31183145 0.42332645]
[0.82770259 0.40919914 0.54959369]]
```

11.5.5 Sample Problem: Finding Paths

We are going to solve a very practical problem: Is there a way to get from point A to point B, and how many steps will it take? Admittedly, a step could be arbitrary, but this problem can be re-coded to find that answer, too. Consider the map in Figure 11.6. This is a simplified version of part of the New York subway system. Ten points have been identified here, and each point has a way to get to some other nearby points directly. An adjacency matrix for this map has a row and a column for each point, and has a 1 if the two points are adjacent and a 0 otherwise. *Adjacency* here means connected with no nodes in between. For example, point 6 is adjacent to points 7 and 5 here. The points represent the following places:

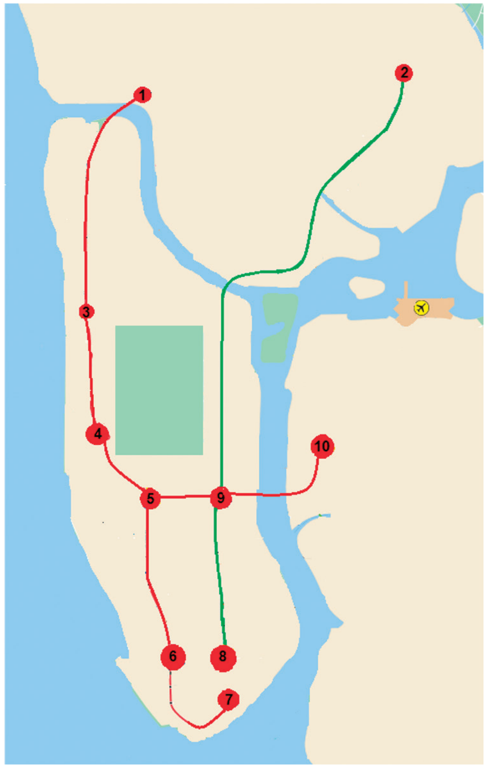


Figure 11.6
Part of the New York subway system.

1. Marble Hill
2. Pelham Bay Park
3. Columbia University
4. Lincoln Center
5. Times Square
6. Chambers Street
7. Wall Street
8. City Hall
9. Grand central
10. Queens Plaza

Is City Hall reachable from Wall Street? Using this map, how many stops are required for the journey?

In the adjacency matrix, we place a 1 if the row and column locations are immediately adjacent and a 0 otherwise. The matrix looks like this:

1	0	1	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	1	0
1	0	1	1	0	0	0	0	0	0
0	0	1	1	1	0	0	0	0	0
0	0	0	1	1	1	0	0	1	0
0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	1	1	0	0	0
0	0	0	0	0	0	0	1	1	0
0	1	0	0	1	0	0	1	1	1
0	0	0	0	0	0	0	0	1	1

The algorithm for finding whether paths exist is not intuitive, but easy to implement using NumPy. When the adjacency matrix is multiplied by itself, the result has non-zero values in locations that represent points that are two steps apart. Multiply it again, and we can find points that are three steps apart, and so on. Using NumPy, this matrix could be initialized as follows:

```
from numpy import *
adj = array( [[1,0,1,0,0,0,0,0,0,0],
         [0,1,0,0,0,0,0,0,1,0],
         [1,0,1,1,0,0,0,0,0,0],
         [0,0,1,1,1,0,0,0,0,0],
         [0,0,0,1,1,1,0,0,1,0],
         [0,0,0,0,1,1,1,0,0,0],
         [0,0,0,0,0,1,1,0,0,0],
         [0,0,0,0,0,0,0,1,1,0],
         [0,1,0,0,1,0,0,1,1,1],
         [0,0,0,0,0,0,0,0,1,1]])
```

Indexing a value in a two-dimensional array requires two indices. The first index references the row desired, and the second references the column. Numpy gives us the matrix multiply operations, so the program is as follows:

```
count = 1
b = adj*adj
while b[6][7] == 0:
    b = adj@b
    count = count + 1
    print (count, b)
    if count > 10:
```

```
            break
    print ("steps: ", count)
```

As usual, the indices are always at 0, so adj[6][7] refers to a connection between points 7 and 8, which means Wall Street and City Hall.

11.5.6 Linear Regression Again

The linear regression program that was written earlier can be written with fewer lines of code, and it will be faster too, if we use NumPy. The array operations make the code more compact. For example, finding the means of the x and y data can be done in one line each if both are NumPy arrays:

```
      mx = x.sum()/len(x)          # Mean X
      my = y.sum()/len(y)          # Mean y
```

The same is true of the standard deviation:

```
sdx = sqrt ( sum ( (x-mx)**2 )/(len(x)-1) )
                                      # standard deviation X
sdy = sqrt ( sum ( (y-my)**2 )/(len(y)-1) )
                                      # standard deviation Y
```

The expression x-mx actually results in a new array in which each element is the corresponding value of the x array with mx, the mean, subtracted from it. (x-mx)**2 squares each element in this array. The code that computes the correlation is also much more compact.

This NumPy implementation is about twice as fast as the original:

```
from numpy import *

def correlate (x, y, meanx, meany):
    a = sum ( (x-meanx)*(y-meany) )
    b = sum ((x-meanx)**2)
    c = sum ((y-meany)**2)
    v = a/sqrt(b*c)
    return v

def regress (x, y):
    mx = x.sum()/len(x)          # Mean X
    my = y.sum()/len(y)          # Mean y
    sdx = sqrt ( sum ( (x-mx)**2 )/(len(x)-1)
                                 )     # standard deviation X
```

```
    sdy = sqrt ( sum ( (y-my)**2 )/(len(y)-1) )
                                    # standard deviation y
    if sdx == 0: return
    r = correlate (x, y, mx, my)
    m = r * sdy/sdx
    b = my - m * mx
    return (m, b)

def err (x, y, m, b):
    return sum(m*x + b - y)

f = open ("treedata.txt", "r")
s = f.readline ()
x = zeros((100))
y = zeros((100))

for j in range(0,100):
    for i in range (1,len(s)):
        if s[i] == ",":
            break
    x[j] = float(s[0:i-1])
    y[j] = float(s[i+1:])
    s = f.readline()

line = regress(x, y)
print ("Equation is y = ", line[0], "*x + ", line[1])
print ("Error is ", err(x,y, line[0], line[1]))
```

11.6 SUMMARY

A discussion of some of the more important problem types studied by scientists was presented along with a method for their solution. The root of an equation is the place where its value is zero, and Newton's method was described as a means of finding a root. Newton's method requires that the derivative of the function be known, so the means of numerically determining the derivative were also discussed.

Since the derivatives could be calculated, we discussed the methods for performing integration and wrote the functions for doing the calculation using the trapezoidal rule.

One of the more common calculations in science is to find an *optimum value* for a function. Another method of Newton's was used to find maxima or minima of a function.

The modeling of data is important in scientific (and other) disciplines. A method for finding the best straight line that passes through a set of data was illustrated (linear regression) and code was designed and tested for this problem.

Evolutionary algorithms can be used to find the optimum of a function, and they are especially useful when dealing with multi-dimensional functions or functions that have many local optima, and when no derivative of the function exists.

Biologists sometimes need to match sequences of DNA. A method that does this using bases as characters and sequences as strings was presented; this is the Smith-Waterman algorithm for local sequence matching, and it is commonly used for these problems.

NumPy is a numerical math package for Python whose main feature is a multi-dimensional array. This implementation has faster execution for mathematical work than lists and tuples, and it implements some convenient vector and matrix operations.

Exercises

1. Modify the root finding example so that a numerical derivative is used instead of an analytical one (i.e., use **derive1()** or **derive2()**). This is a more practical situation. What is the effect?
2. Modify the **trap0()** function in the trapezoid rule example so that it never calls the function being evaluated more than once for any point.
3. Look up *Simpson's Rule* and code your own version. Compare it with the trapezoid rule for two functions of your choice. Which one is more accurate after each iteration?
4. Write a function **error()** that accepts X and Y data tuples, and values **a** and **b**. It returns the total error between the data points and the curve **ax**2+**bx**. Write it using NumPy and without using NumPy.

5. The (natural) logarithm of a value v is defined to be the integral of 1/x from 1 to v. Create a function that calculates the natural log using the existing integration function.

6. Run the evolutionary algorithm to optimize the Goldstein-Price twenty times. Does it ever fail to approach the minimum? How often? What can be done if an EA does not arrive at an optimum, and how can it be determined?

7. Using software developed in this chapter, find two positive numbers whose sum is 9 and so that the product of one number and the square of the other number is a maximum.

$$Max\ P = x\, y^2 = x\,(9-x)^2$$

Notes and Other Resources

Online edit distance calculator: *http://planetcalc.com/1721/*

Smith-Waterman algorithm:

http://www.slideshare.net/avrilcoghlan/the-smith-waterman-algorithm

https://www.youtube.com/watch?v=jrJ23aaByE8

Warshall's algorithm: *https://cs.winona.edu/lin/cs440/ch08-2.pdf*

NumPy: *https://numpy.org/doc/1.18/contents.html*

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Chapter 12

How To Write Good Programs

In this chapter

There is no general agreement on how best to put together a good program. A good program is functionally correct, readable, modifiable, reasonably efficient, and solves a problem that someone needs solved. This chapter is distinct from the others in this book because of the more personal nature of the subject material. Writing code for some people is like telling a story or making a painting: it's not that it is art, but it is personal. If you wish to insult a programmer, say that their code is poorly structured, or naïve, or in some way less than adequate.

There are many processes that have been described for programming, and the truth is that not only is there not one *best* one, but it is rarely certain than any of them is better than any of the others. When someone writes a program, they are trying to solve a problem. What they are doing is translating a loose collection of ideas into a form that can be represented on a computer, which is to say as numbers. The ideas are associated with algorithms, things that can be shown to work for at least a range of situations. Then that needs to be converted into a sequence of steps that leads to a solution to the original problem.

This is in part a problem in *synthesis*, the combining of separate components, elements, and ideas into a coherent whole. There is something called *synthesis programming*, but that's not what we will discuss here. The parts of a program include decision constructs (IF statements), looping (FOR and WHILE), expressions, assignment statements, and data structures (such as tuples, dictionaries, and strings). There is a degree of skill involved in using these units to build a sensible larger program. This skill is somewhat individual. No two programmers will create exactly the same program for a non-trivial problem.

What we're going to do in this chapter is show the development of an entire computer program, with all of the intermediate steps, flaws, errors, and flashes of genius (if any). Why? The answer is because that is rarely done in lectures or in a book. When teaching mathematics, the professor often shows the proof of a theorem on the blackboard (or as PowerPoint) and explains the steps. What they never do is show how the theorem was actually proved when the original person proved it—dead ends, days of no progress, good ideas, and bad ideas.

This is crucial. No theorem and no computer program flows fully formed and correct from someone's head. Observing the full process is a valuable stage in the education of a programmer. They can see that the process is prone to error, even for good programmers. They can see that not all ideas that seem good are actually good, and that the process is not a linear one, but that it appears in some sense to spiral, gaining functionality at each loop. They can see that there can be a simple and obvious method that could be agreed upon by many different programmers and yet adapted for each new situation. The method that we use here is called *iterative refinement*, and it is nearly independent of language or philosophy.

One example program is a computer game, and one that can't be played without a computer. It is a breakout style game that uses circles instead of rectangles. The other is a system that formats typed text.

12.1 PROCEDURAL PROGRAMMING – WORD PROCESSING

In the early days of desktop publishing, the programs that writers used did not display the results on the screen in "what-you-see-is-what-you-get" form. Formatting commands were embedded within the text and were implemented by the program, which would create a printable version that was properly formatted.

Programs like *roff*, *nroff*, and *tex* are still used, but most writing tools now look like *Word* or *PageMaker* with commands being given through a graphical user interface.

There is a limit to what kind of text processing can be done using simple text files, but when you think about it, that's really what a typewriter produces—simple text on paper with fixed size fonts.

The program developed here accepts text from a file and formats it according to a set of commands that have a specific format and are predefined by the system. The input resembles that accepted by *nroff*, an old Unix utility, but is a subset for simplicity. Since it uses standard text input and output, measurements are made in characters, not inches or points. Commands begin on a new line with a "." character and are alphabetic. A line beginning with ".br," for instance, results in a forced line break. Some commands take a parameter: the command ".ll 55" sets the line length to 55 characters.

Here is a list of all of the commands that the system recognizes:

.pl n	Sets the page length to n lines
.bp n	Begin page n
.br	Break
.fi	Fill output lines (e.g., justify)
.nf	Don't fill output lines
.na	No justification
.ce n	Center the next n input lines
.ls n	Output n-1 line spaces after each line
.ll n	Line length is n characters
.in n	Indent n characters
.ti n	Temporarily indent n characters
.nh	Do not hyphenate
.hy	Hyphenation on
.sp n	Generate n lines

The program reads a text file and identifies the words and the commands. The words are written to an output file formatted as described by the commands. The default is to right justify the text and to use empty lines as paragraph breaks. The questions to be answered here are as follows:

1. How does one begin creating such a program?

2. Can the process of program creation be described?
    a. Is the process systematic or casual?
    b. Is there only one process?

Beginning with the last question first, there is *no* single process. What is presented here is only one, but it should be understood that there are others, and that some processes probably work better than others for some kinds of program. The program we create here does not use classes, and it involves a classical or traditional methodology generally referred to as *top-down*. Some people only use object-oriented code, but a problem with teaching that way is that a class contains traditional, procedure-oriented code. *To make a class, one must first know how to write a program.*

12.1.1 Top-Down

In top-down programming, the higher levels of abstraction are described first. A description of what the entire program is to do is written in a kind of English/computer hybrid language (*pseudocode*), and this description involves making calls to functions that have not yet been written but whose function is known. When the highest level description is acceptable, then the functions used are described. In this way, the high-level decisions are described in terms of the lower levels, whose implementation is postponed until the details are appropriate. The process repeats until all parts have been described, at which time the translation of the pseudocode into a real programming language can proceed, and should be straightforward. This can result in many distinct programs, but they all should do basically the same thing.

For the task at hand, the first step is to sketch the actions of the program as a whole. The program begins by opening the text file and opening an output file. The basic action is to copy from input to output, with certain additions to the output text. The data file is read in as characters or words, but output as lines and pages. The following is an example:

Open input file **inf**

Open output file **outf**

Read a word **w** from **inf**

While there is more text on **inf**:

If **w** is a command:

Process the command w

Else:

The next word is **w**. **Process** it

Read a word from **inf**

Close **inf**

Close **outf**

This represents the entire program, although the code lacks much detail. As Python code, this would look almost the same:

```
filename = input ("PYROFF: Enter the name if the input
                   file: ")
inf = open (filename, "r")
outf = open ("pyroff.txt. "w")
w = getword (inf)
while w != "":
    if iscommand(w):
        process_command (w)
    else:
        process_word (w)
    w = getword(inf)
inf.close()
outf.close()
```

The functions must exist for the program to compile them. They should initially be *stubs*, relatively non-functional, but resulting in output:

```
from random import *

def getword (f):
    print ("Getword ")

def iscommand(w):
    print ("ISCOMMAND given ", w)
    if random()< 0.5:
        return False
    return True

def process_command (w):
    print ("Processing command ", w)
```

```
def process_word (w):
    print ("Processing the word ", w)
```

This program will run, but it never ends because it never reads the file. Still, we have a structure.

Now the functions need to be defined, and in the process, further design decisions are made. Consider **getword()**: what comprises a *word* and how does it differ from a *command*? A command starts at the beginning of a line with a "." character. It is followed by two alphabetic characters that are defined by the system. If the two characters do not match any combinations in the list of commands, then it is not a command. A word begins or ends with a white space (blank, tab, or end of line) and contains all of the characters between those white spaces. It may not be a word in the traditional sense, in that it may not be an English word; it could be a number or other sequence of characters. Those may cause problems, but it will be left up to the user to figure it out (for example, a long URL may extend over a line). The program has to do something, and so will probably put an end of line when the count of characters exceeds a maximum and leave the problem to the user to fix.

Let's figure out the **getword()** function. It constructs a word as a character string from individual characters that have been read from the input file. A first try could be as follows:

```
def getword(f):
    w = ""
    while whitespace(ch(f)):
        nextch(f)
    while not whitespace(ch(f)):
        w = w + ch(f)
        nextch(f)
    print ("Getword is ", w)
    return w
```

The function **whitespace()** returns **True** if its parameter is a white space character. The function **nextch()** reads the next character from the specified file, and the function **ch()** returns the value of the current character. To effectively test **getword()**, we need to implement these three functions. Here's a first attempt:

```
def whitespace (c):
    if c == " ": return True
    if c == "\t": return True
```

```
        if c == "\n": return True
        return False

    def ch(f):
        global c
        return (c)

    def nextch(f):
        global c
        c = f.read(1)
```

This way of handling input is unusual, but there is a reason for it. We are anticipating a need to buffer characters or to place them back on the input stream. It is similar to the input scheme used in Pascal, or the system found in early forms of UNIX which used **getchar – putchar - ungetc**. The necessity of extracting commands from the input stream, and that commands must begin a new line, might make this particular scheme useful. The initial implementation of **nextch()** simply reads a new character from the file, but it could easily be modified to extract a character from a buffer, and refile the buffer if it is empty. Both would look the same to the programmer using them.

The program runs, but has a problem: it never terminates. After the text file has been read, the program seems to call **nextch()** repeatedly. After some thought the reason is clear—when the input request results in an empty string (“”), the current character is not a white space, and the loop in **getword()** that is building a word runs forever. This is a traditional end-of-file problem and can be solved in a few different ways: a special character can be used for EOF, a flag can be set, or the empty string can be tested for in the loop explicitly. The latter solution was chosen, and fixes the infinite loop. The word construction loop in **getword()** becomes

```
while not whitespace(ch(f)) and ch(f) !="":
```

A possible next step is to distinguish between commands and words. There are two things to do because a command starts a line and begins with a period (.): mark the beginning of a new line, and look up the input string in a table of commands. The command could be searched first, then if it matches a command name, we could back up the input to see if it was preceded by a newline character (“\n”). A newline counts as a white space, and another option would be to set a flag when a newline character is seen, clearing it when another character is read in. Now a string is a command if the flag set before it was read in and it matches one of the commands. Timing is important in this method, but white space separates words, so it could work by simply remembering (saving) the last white space character seen before any word.

This code has a problem. When implemented, none of the commands are recognized. A table of names was implemented as a tuple:

```
table = (".pl",".bp",".br",".fi",".nf",".na",".ce",
         ".ls",".ll",".in",".ti",".nh",".hy",".sp")
```

The **nextch()** function was modified so

```
def nextch(f):
    global c, lastws
    c = f.read(1)
    if whitespace(c):
        lastws = c
```

and the function **iscommand()** is implemented by checking for the newline and the match of the string in the table:

```
def iscommand(w):
    global table, lastws
    if lastws == "\n":
        if w in table:
            return True
    return False
```

To discover the problem, some print statements were inserted that show the previous white space character and the match in the table for all calls to **iscommand()**. The problem, which should have been obvious, is that when the command is read in, the last white space seen will be the one that *terminated* it, not the one in front of it.

A solution: keeping the same theme of remembering white space characters, let's save the previous *two* white space characters seen. The most recent white space is the one that terminated the word string, and the second most recent will always be the one before it. All of the others, if any, would have been skipped within **getword()**. The solution, as coded in the **nextch()** function, is as follows:

```
def nextch(f):
    global c, clast, c2last
    c = f.read(1)
```

```
        if whitespace(c):
            c2last = clast
            clast = c
```

There are two variables needed, **clast** being the previous white space and **c2last** being the one encountered before **clast**. Now **iscommand()** is modified slightly to look for **c2last**:

```
    def iscommand(w):
        global table, c2last
        if c2last == "\n":
            if w in table:
                return True
        return False
```

This code identifies the commands in the source file, even the text that looks like a command but is not: ".xx."

Notice that the development of the program consists of an initial sketch and then filling in the code as stubs and coding the stubs to be functional code, one at a time. Sometimes a stub requires further undefined functions to be used, and those could be coded as stubs too, or completed if they are small so as to allow testing to proceed. It's a judgment call as to whether to complete the stubs down the chain for one part of the program or to proceed to the next one at the current level. For example, should we have completed the **nextch() and ch()** functions before trying to design **process_command()**? It does depend on how testing can proceed and what level we are at. The **nextch()** function looks like it won't call other functions that have not been implemented, and it is difficult to test **getword()** without finishing **nextch()**.

This discussion speaks to what the next step will be from here, and there could be many. Let's look at commands next, because they will dictate the output, and then deal with formatting last. It is known that a string represents a command, and the function called as a consequence is **process_command()**. This function must determine which command string was seen and what to do about it. The way commands are handled and the way the output document is specified has to be sorted out before this function can be finished, but a set of stubs can hold the place of future decisions as before.

The string that was seen to be a command is stored in a tuple. The index of the string within the tuple tells us which command was seen, although a string match could be done directly. Using a tuple is better because new commands can always be added to the end of the tuple during future modifications and it is easier to modify command names. The function, which used to be a stub, is now

```
def process_command (w):
    global table, inf, page_length, fill, center,
       center_count,
    global spacing, line_length, adjust, hyphenate
    k = table.index(w)
    if k == 0:                 # .PL
        s = getword(inf)
        page_length = int(s)
    elif k == 1:               # .BP
        genpage()
    elif k == 2:               # .BR
        genline()
    elif k == 3:               # .FI
        fill = True
    elif k == 4:               # .NF
        fill == False
    elif k == 5:               # .NA
        adjust = False
    elif k == 6:               # .CE
        center = True
        s = getword(inf)
        center_count = int(s)
    elif k == 7:               # .LS
        s = getword(inf)
        spacing = int(s)
    elif k == 8:               # .LL
        s = getword(inf)
        line_length = int(s)
        print ("Line length ", line_length, "characters")
    elif k == 9:               # .IN
        s = getword(inf)
        indent (int(s))
    elif k == 10:              # .TI
        s = getword(inf)
        temp_indent (int(s))
    elif k == 11:              # .NF
        hyphenate = False
    elif k == 12:              # .HY
        hyphenate = True
```

```
elif k == 13:               # .TL
    dotl ()
elif k == 14:               # .SP
    s = getword(inf)
    space (int(k))
```

This completes iteration 5 of the system and generates quite a few new stubs and defines how some of the output functions will operate. There are some flags (**hyphenate**, **center**, **fill**, and **adjust**) and some parameters for the output process (**line_length** and **spacing**) that are set, and so will be used in sending output text to the file. These parameters being known, it is time to define the output process, which is implemented starting with the function **process_word()**.

As mentioned earlier, the program reads data one character at a time and emits it as words. There is a specified line length, and words can be read and stored until that length is neared or exceeded. Words could be stored in a string. When the line length is reached, the string could be written to the file. If right justification is being done, spaces could be added to some other spaces in the string until the line length was met exactly, or the final word could be hyphenated to meet the line length. If right justification is not being done, then the line length only has to be approached, but not exceeded.

For text centering, input lines are padded with equal numbers of spaces on both sides. The page size is met by counting lines, and then by creating a new page when the page size is met, possibly by entering a form feed or perhaps by printing empty lines until a specified count is reached. Indenting is simple: the **in** command results in a fixed number of spaces being placed at the beginning of each output line; the **ti** command results in a specified number of spaces being placed at the beginning of the current line. Hyphenation is done by table lookup. Certain suffixes and prefixes and letter combinations are possible locations for a hyphen. The final word on a line can be hyphenated if a location within it is subject to a hyphen as indicated by the table.

The process is to read and build words and copy them to a string, the next output line. No action is taken until the string nears the line length, at which point insertion of spaces, hyphenation, or other actions may be taken to make the string fit the line, either closely or precisely. After a line meets the size needed, it is written, perhaps followed by others if the line spacing is larger than one. The basic action of the **process_word()** function is to copy the word to a string, the output buffer, under the control of a set of variables that are defined by the user through commands:

page_length	55	Number of lines of text on a single page
fill	True	Controls whether the text is being formatted
adjust	True	Controls whether the text is right justified
center	False	Controls whether text is being centered
center_count	0	Number of lines still to be centered
spacing	1	Number of lines output per line of text
nindent	0	Number of spaces on the left
line_length	66	Number of characters on one line
hyphenate	True	Are words hyphenated by the system?

The simplest version of **process_word()** copies words to the buffer until the line is full and then writes that line to the output file.

```
def process_word (w):
    global buffer, line_length
    if len(buffer) + len(w) + 1 <= line_length:
        buffer = buffer + " " + w
    else:
        emit(buffer)
        buffer = w
```

The code above adds the given word plus a space to the buffer if there is room. Otherwise, it calls the **emit()** function to write the buffer to the output file and places the word at the beginning of a new line. This is nearly correct. Some of the output for the sample source is as follows:

This is sample text for testing Pyroff. The default is to right
adjust continuously, but embedded commands can change this.
Now the line width should be
30 characters, and so the left
margin is pulled back. This
line is centered .xx not a
command. Indented 4

Note that the command ".ll 30" was correctly handled, but that there is an extra space at the beginning of the first line. That's due to the fact that **process_word()**

adds a space between words, and if the buffer is empty that space gets placed at the beginning. The solution is to check for an empty buffer:

```
if len(buffer) + len(w) + 1 <= line_length:
    if len(buffer) > 0:
        buffer = buffer + " " + w
    else:
        buffer = w
```

This was a successful fix, and completes iteration 6 of the system, which is now 150 lines long.

Within **process_word()**, there are multiple options for how words can be written to the output. What has been done so far amounts to *filling* but no *right justification*. Other options are *no filling*, *centering*, and *justification*. When the filling is turned off, an input line becomes an output line. This is true for centering as well. When justification is taking place, the program will make the output lines exactly **line_length** characters long by inserting spaces in the line to extend it and by hyphenation, where permitted, to shorten it. The rule is that the line must be the correct length and must not begin or end with a space. The implementation of this part of the program is at the heart of the overall system, but would not be possible without a sensible design up to this point.

12.1.2 Centering

First, a centered line is to be written to output when an end of line is seen on input. This means that the **clast** variable is used to identify the end of line and to emit the text. Next, the line has spaces added to the beginning and end to center it. The buffer holds the line to be written and has **len(buffer)** characters. The number of spaces to be added totals **line_length – len(buffer)**, and half are added to the beginning of the line and half to the end. A function that centers a given string would be as follows:

```
def do_center (s):
    global line_length
    k = len(s)              # How long is the string?
    b1 = line_length - k    # How much shorter than the line?
    b2 = b1//2              # Split that amount in two
    b1 = line_length - k - b2
    s = " "*b1 + s + " "*b2   # Add spaces to center the text
    emit(s)                   # Write to file
```

In the **process_word()** function, some code must be added to handle centering. This code has to detect the end of line and pass the buffer to **do_center()**. It also counts the lines, because the ".ce" command specifies a number of lines to be centered.

```
if center:                      # Text is being centered, no fill
    if len(buffer) > 0:               # Add this word to the line
        buffer = buffer + " " + w
    else:
        buffer = w
    if clast == "\n":        # An input line = an output line
        do_center(buffer)                # Emit the text
        center_count = center_count - 1  # Count lines
        if center_count <= 0:            # Done?
           center = False            # Yes. Stop centering.
```

This code is not quite enough. There are two problems observed. One problem is that the buffer could be partly full when the ".ce" command is seen, and must be emptied. This problem is serious, because filling may be taking place and the line might have to be justified. For the moment, a call to **emit()** happens when the ".ce" command is seen, but this will have to be expanded.

The other problem is simpler: the **do_center()** function does not empty the buffer, so the line being centered occurs twice in the output. For example,

Margin is pulled back.

This line is centered ← This is correct

This line is centered .xx not ← This is wrong. Text is repeated.

a command. Indented 4

The solution is to clear the buffer after **do_center()** is called:

```
do_center(buffer)                # Emit the text
buffer = ""                      # Clear the buffer
```

12.1.3 Right Justification

Centering text is a first step to understanding how to justify it. Right justified text has the sentences arranged so that the right margin is aligned to the line. When centering, spaces are added to the left and right ends of the string so as to place any text in the middle of the line. When justifying, any space in the line can be made into multiple spaces, thus extending the text until it reaches the right margin. Naturally it would not be acceptable to place all of the needed spaces in one spot. It looks best if they are distributed as evenly as possible. However, no matter what is done, there will be some situations that cause ugly spacing.

The number of spaces needed to fill up a line is **line_length – len(buffer)**, just as it was when centering. As words are added to the line, this value becomes smaller. When it is smaller than the length of the next word to be added, then the extra spaces must be added and a new line started. That is, when

```
k = line_length - len(buffer)
if k  <  len(word):
```

then adjusting is performed. First, count the spaces in the buffer and call this **nspaces**. If **k>nspaces**, then change each single space into **k//nspaces** space characters and set **k = k%nspaces**. This will rarely happen. Now, we need to change *some* of the spaces in the buffer into double spaces. Which ones? In an attempt to spread them around, set **xk = k + k//2**. This will be used as an increment to find consecutive spots to put spaces. So for example, let **k = 5**, in which case **xk = 7**. The first space could be placed in the middle, or at space number 2. Now count **xk** positions from 2, starting over at zero when you hit the end. This will give 4 as the next position, followed by 1, then 3, and then 0. This process seems to spread them out. Now the buffer is written out and the new word is placed in an empty buffer.

This sounds tricky, so let's work through it. Never enter code that is not likely to work! Inside of the **process_word()** function, check to see if adjusting is going on. If so, check to see if the current word fits in the current line. If so, put it there and move on.

```
elif adjust:
    k = line_length - len(buffer)    # Number of spaces
                                     # remaining
    if k  > len(w):                  # Does the word w fit?
        if len(buffer) == 0:         # Yes. Empty buffer?
            buffer = w               # Yes. Buffer = word.
        else:                        # No. Add word to the
                                     # buffer
            buffer = buffer + " " + w
        print ("Buffer now ", buffer, k, len(w))
    else:                          # Not enough space remains
```

```
        print (buffer, k, w, len(w))
        nspaces = buffer.count(" ") # How many spaces in
                                    # buffer?
        xk = k + k//2 +1            # Space insert increment
        while k > 0:
            i = nth_space (buffer, xk)
            buffer = buffer[0:i] + " " + buffer[i:]
            k = k - 1
            xk = xk + 1
        emit(buffer)
        buffer = w
```

The function **nth_space (buffer, xk)** locates the **n**th space character in the string **s** modulo the string length. The spaces were not well distributed with this code in some cases. There was a suspicion that it depended on whether the number of remaining spaces was even or odd, so the code was modified to read

```
    .  .  .
xk = k + (k+1)//2               # Space insert increment
if k%2 == 0:
    xk = xk + 1
    .  .  .
```

which worked better. The output for the first part of the test data was as follows:

```
This is sample text for    testing Pyroff. The default is
to right adjust continuously, but embedded commands can
change this.
Now the line width   should be
30 characters, and so the left
margin is pulled back.
     This line is centered
.xx not  a command. Indented 4
characters.  The  idea  behind
top-down  programming is  that
the     higher    levels    of
abstraction are      described
          .  .  .
```

The short lines are right justified, but the distribution of the spaces could still be better.

The function **nth_space()** is important, and looks like this:

```
def nth_space (s, n):
    global nindent
    nn = 0      # nn is a count of spaces seen so far
    i = 0       # i is the index of the character being
                # examined
    while True:
        if s[i] == " ":      # Is character i a space?
            nn = nn + 1      # Yes. Count it
        if nn >= n:          # Is this enough spaces?
            return i         # Yes, return the location
       i = (i + 1)%len(s)  # Next i, wrapping around the end
```

12.1.4 Other Commands

The rest of the commands have to do with hyphenation, pagination, and indentation, except for the ".br" command. Dealing with the indentation first, the command ".in" specifies a number of characters to indent, as does ".ti." The ".in" command begins indenting lines from the current point on, whereas ".ti" only indents the next line. Since the ".ti" command only indents the next line of text, perhaps initializing the buffer to the correct number of spaces will be the right approach. The rest of the text for the line will be concatenated to the spaces, resulting in an indented line.

The ".in" command currently results in the setting of a variable named **nindent** to the number of spaces to be indented. Following the suggestion for a temporary indent, why not replace all initializations of the buffer with indented ones? There are multiple locations within the **process_word()** function where the buffer is set to the next word:

```
buffer = w
```

These could be changed to

```
buffer = " "*nindent +w
```

This sounds clean and simple, but it fails miserably. Here is what it looks like. For the input text, we have

```
Indented    4   characters.
.in 2
The idea behind top-down programming is that the higher
levels of abstraction are described first. A description
```

```
of what he entire program is to do is written in a kind-of
English/computer hybrid language (pseudocode), and this
description involves making calls to functions that have
not yet been written but whose function is known.
```

We get the following results:

```
Indented    4  characters. The
        idea  behind top-down
    programming  is that   the
  higher levels of abstraction
    are  described  first.   A
    description  of  what   he
  entire program   is to do is
      written    in  a kind-of
      English/computer  hybrid
  language (pseudocode),   and
   this description   involves
  making calls to    functions
    that  have  not yet   been
```

Can you figure out where the problem is by looking at the output? This is a skill that develops as you read more code, write more code, and design more code. There is a place in the program that will add spaces to the text, and clearly that has been done here. It is how the text is right adjusted. The spaces are counted and sometimes replaced with double spaces. This happened here to some of the spaces used to implement the indent.

Possible solutions include the use of special characters instead of leading blanks, to be replaced when printed; finding another way to implement indenting; modifying the way right adjusting is done. Because the number of spaces at the beginning of the line is known, the latter should be possible: when counting spaces in the adjustment process, skip the **nspaces** characters at the beginning of the line. This is a modification to the function **nth_character()** to position the count after the indent:

```
def nth_space (s, n):
    global nindent
    nn = 0
    i = 0
    while True:
        print ("nn=", nn)
```

```
if s[i] == " ":
    nn = nn + 1
    print ('" "')
if nn >= n:
    return i
i = (i + 1)%len(s)
if i < nindent+tempindent:          ←
    i = nindent+tempindent          ←
```

A second problem in the indentation code is that there should be a line break when the command is seen. This is a matter of writing the buffer and then clearing it. This should also occur when a temporary indent occurs, but before it inserts the spaces. The temporary indent will have the same problem as the indent with respect to the right adjustment, and we have not dealt with that.

The line break can be handled with a new function:

```
def lbreak ():
    global buffer, tempindent, nindent
    if len(buffer) > 0:
        emit(buffer)
    buffer = " "*(nindent+tempindent)
    tempindent = 0
```

The break involves writing the buffer and clearing it. Clearing it also means setting the indentation. Because this sequence of operations happens elsewhere in the program, those sequences can be replaced by a call to **lbreak()**. Note that a new variable **tempindent** has been added; it holds the number of spaces for a temporary indentation, and it is added to the regular **nindent** value everywhere that a variable is used to obtain the total indentation for a line. Now the right adjustment of a temporarily indented line should work.

The **lbreak()** function is used directly to implement the ".br" command. A stub previously named **genline()** can be removed and replaced by a call to **lbreak()**.

Line spacing can be handled in **emit()**, which is where lines are written to the output file. After the current buffer is written, a number of newline characters are written to equal the correct line spacing. The new **emit()** function is

```
def emit (s):
    global outf, lines, tempindent, spacing, page_length
```

```
        outf.write(s+"\n")
        lines = (lines + 1)%page_length
        for i in range (1, spacing):
            outf.write ("\n")
            lines = (lines + 1)%page_length
        tempindent = 0
```

What about pages? There is a command that deals with pages directly, and that is ".bp," which starts a new page. The page length is known in terms of the number of lines, and **emit** counts the lines as it writes them. Implementing the ".bp" command should be a matter of emitting the number of lines needed to complete the current page. The code looks like this:

```
    def genpage():
        global page_length, lines
        lbreak()
        for i in range (lines, page_length):
            emit ("")
```

All that is missing is the ability to hyphenate, which is left as one of the exercises. The system appears to do what is needed using the small test file, so the time has come to construct more thorough tests. The file "preface.txt" holds the text for the preface of a book named *Practical Computer Vision Using C*. This book was written using *Nroff*, and the commands not available in Pyroff were removed from the source text so that it could be used as test data. It consists of over 500 lines of text. The result of the first try with this program was interesting.

Pyroff appeared to run using this input file, but never terminated. No output file was created. The first step was to try to see where it was having trouble, so a print statement was added to show what word had been processed last. That word was "spectrograms," and it appears in the first paragraph of text, after headings and such. Now the data that caused the problem is known. What is the program doing? There must be an unterminated loop someplace. Putting prints in likely spots identifies the culprit as the loop in the **nth_space()** function. Tracing through that loop finds an odd thing: the value of **nindent** becomes negative, and that causes the loop never to terminate. The test data contained a situation that caused the program to fail, and that situation resulted from a difference between *Nroff* and pyroff: in *Nroff* the command '.in -4' subtracts 4 from the current indentation, whereas in pyroff it sets the current indent to -4.

This kind of error is very common. All values entered by a user must be tested against the legal bounds for that variable. This was not done here, and the fix is simple. However, it reminds us to do that for all other user input values. These are processed in the function **process_command()**, so locating those values is easy. Once this was done things worked pretty well. There was one problem observed, and that was an indentation error. Consider the input text:

```
.nf
1. Introduction
.in 3
1.1 Images as digital objects
1.2 Image storage and display
1.3 Image acquisition
1.4 Image types and applications
```

The program formats this text as follows:

```
1. Introduction
    1.1 Images as digital objects
   1.2 Image storage and display
   1.3 Image acquisition
   1.4 Image types and applications
```

There is an extra space in the first line after the indent. This seems like it should be easy to find where the problem is, but the function that implements the command, **indent()**, looks fine. However, on careful examination (and printing some buffer values), it can be seen that it should not call **lbreak()** because that function sets the buffer to the properly indented number of space characters. This means that when the later tests for an empty buffer occur, the buffer is not empty and text is appended to it rather than being simply assigned to it. That is, for an empty buffer the first word is placed into it:

```
buffer = word
```

whereas, if text is present, the word is appended after adding a space:

```
buffer = buffer + " " + word
```

The indent function now looks like this:

```
def indent (n):
    global nindent, buffer
    nindent = n
```

```
    emit(buffer)
    buffer = ""
```

The preface is now formatted well. Other problems may exist, and these should be reported to the author and publisher when discovered. (The book's wiki is the place for such discussions.)

12.2 OBJECT ORIENTED PROGRAMMING – *BREAKOUT*

The original game named *Breakout* was built in 1976, conceived by Nolan Bushnell and Steve Bristow and built by Steve Wozniak (some say aided by Steve Jobs). In this game, there are layers of colored rectangles in the upper part of the screen. A simulated ball moves around the game window, and if it hits a rectangle, it accumulates points and bounces. The ball also bounces off of the top and sides of the window, but will pass through the bottom and be lost unless the player moves a paddle into its path. If so, the ball will bounce back up and perhaps score more points; if not, the ball moves out of play. After a fixed number of balls are lost, the game is over.

The game being developed here uses circles, that we call *tiles*, rather than rectangles. There will be 5 rows of tiles, each of a different color and point value: 5, 10, 15, 10, and 5 points for each row respectively. That way the most concealed row has the most points. The player gets three balls to try to clear all of the tiles away. The paddle moves left when the left arrow key is pressed and right when the right arrow key is pressed. The speed of the ball and of the paddle are determined when the game is tested. A sound plays when a tile is removed, when the ball hits the side or top of the window, when the ball hits the paddle, and when the ball is lost. The current score and the number of balls remaining are displayed on the screen someplace at all times.

Figure 12.1 shows an example of a breakout game clone on the left, with rectangular bricks. The picture with the circles is a possible example of how the game that we're developing here might look.

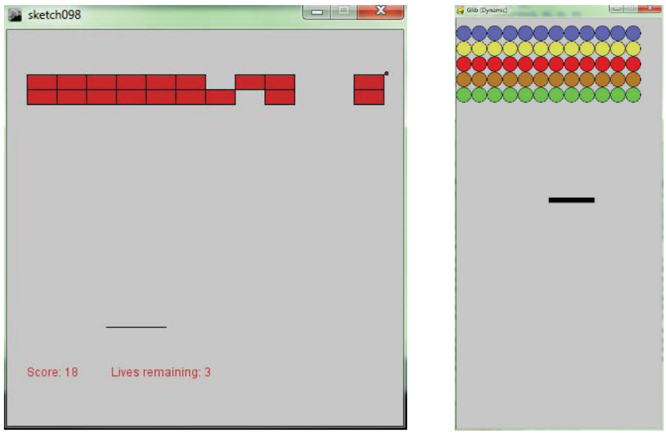


Figure 12.1
Variations on the game Breakout.

12.3 DESCRIBING THE PROBLEM AS A PROCESS

The first step is to write down a step-by-step description of how the program might operate. This may be changed as it is expanded, but we have to start someplace. A problem occurs almost immediately: is the program to be a class? Functions? Does it use pygame?

This decision can be postponed a little while, but in most cases, a program is not a class. It is more likely to be a collection of classes operated by a mail program. However, if object orientation is a logical structure, and it often is, it should evolve naturally from the way the problem is organized and not impose itself on the solution.

The game consists of multiple things that interact. Play is a consequence of the behavior of those things. For example, the ball will collide with a tile resulting in some points, the tile disappearing, and a bounce. The next event may be that the ball collides with a wall, or bounces off of the paddle. The game is a set of managed events and consequences. This makes it appear as if an object oriented design and implementation would be suitable. The ball, each time, and the paddle could be objects (class instances) and could interact with each other under the supervision of a main program which kept track of all objects, time, scores, and other details.

Let's just focus on the gameplay part of the game, and ignore the introductory windows and high score lists and other parts of a real game. The game starts with an initial set up of the objects. The tiles are placed in their start locations, the paddle is placed, the locations of the walls are defined, and then these will be drawn. The initial setup was originally drawn on paper and then a sample rendering was made, shown in Figure 12.1. The code that draws this is as follows:

```
import pygame

width = 400
height = 800
screen = pygame.display.set_mode((width, height))
clock = pygame.time.Clock()
pygame.init()
FPS = 30

for i in range(0, 12):
    pygame.draw.circle(screen, (100, 100, 240), (i*30+15,
                       30), 15)
for i in range(0, 12):
    pygame.draw.circle(screen, (220, 220, 90), (i*30+15,
                       60), 15)
for i in range (0, 12):
    pygame.draw.circle(screen, (220, 0, 0), (i*30+15, 90),
                       15)
for i in range(0, 12):
    pygame.draw.circle(screen, (180, 120, 30), (i*30+15,
                       120), 15)
for i in range(0, 12):
    pygame.draw.circle(screen, (90, 220, 8), (i*30+15,
                       150), 15)
pygame.draw.rect(screen, (0,0,0),  (180, 350,  90, 10))

while True:
    clock.tick(FPS)
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            quit()
    pygame.display.update()
```

This code is just for a visual examination of the potential play area. The first one is always wrong, and this one is too, but it allows us to see why it is wrong and to define a more reasonable set of parameters. In this case, the tiles don't fully occupy the horizontal region and the tile groups are too close to the top, because we want to allow a ball to bounce between the top row and the top of the play area. The play area is too large vertically. Fixing these problems is a simple matter of modifying the coordinates of some of the objects. This code is not a part of the final result. It's common, especially in programs involving a lot of graphics, to test the visual results periodically, and to write some testing programs to help with this.

This program already has some obvious objects: a tile is an object, and so are the paddle and the ball. These objects have some obvious properties too: a tile has a position in x,y coordinates, and it has a color and a size. It has a method to draw it on the screen, and a way to tell if it has been removed or if it still active. The paddle has a position and size, and so does the ball, although the ball has not been seen yet.

What does the main program look like if these are the principal objects in the design? The first sketch is abstract and depends on many functions that have not been written. This code shows the way the classes and the remainder of the code will interact and partly defines the methods they will implement. The initialization step involves creating rows of tiles that will appear much like those in the initial rendering above, but actually consist of five rows of tile objects. This will be done from the function **initialize()**, but each row should be created in a **for** loop:

```
for i in range (0, 12):
    tiles = tiles + tile(i*30+15, y, thiscolor, npoints)
```

where the tile will be created and is passed its x,y position, color, and number of points. The entire collection of tiles is placed into a tuple named **tiles**. The ball will be created at a random location and with a random speed within the space between the paddle and the tiles, and the paddle will be created so that is initially is drawn in the horizontal center near the bottom of the window.

```
def initialize ():
    score = 0
    nballs = 2
    b = ball ()                # Create the ball
    p = paddle ()              # create the paddle
    thiscolor = (100,100,240)  # Blue
    npoints = 5                # Top row is 5 points each
```

```
    for i in range (0, 12):
        tiles = tiles + tile(i*30+15, y, thiscolor, npoints)
    # and so on for 4 more rows
```

The main **draw()** function calls the **draw()** methods of each of the class instances, and they draw themselves:

```
def draw():
    global tiles,p,b
    screen.fill((200, 200, 200))
    # Tiles
    for k in tiles:
        k.draw()
# Paddle
    p.draw()
# Ball
    b.draw()
```

When this function is called (many times each second), the ball is placed in its new position, possibly following a bounce, and then it is drawn. The paddle is drawn, and if it is to be moved it will be done through the user pressing a key. Then the active tiles are drawn, and the messages are drawn on the screen. The structure of the main part of the program is defined by the organization of the classes.

12.3.1 Initial Coding for a Tile

A tile has a graphical representation on the screen, but it is more complex than that. It can collide with a ball and has a color and a point value. All of these aspects of the tile have to be coded as a part of its class. In addition, a tile can be *active*, meaning that it appears on the screen and can collide with the ball, or *inactive*, meaning that the ball has hit it and it is out of play for all intents and purposes. Here's an initial version:

```
class tile:
    def __init__(self, x, y, color, points):
        self.x = x
        self.y = y
        self.color = color
        self.points = points
        self.active = True
        self.size = 30
```

```
def draw(self):
    if self.active:
       pygame.draw.circle(screen, (self.color[0],
       self.color[1], self.color[2]), (int(self.x),
       int(self.y)), self.size // 2)  # Ball is a circle
```

At the beginning of the game, every tile must be created and initialized with its proper position, color, and point value. Then the **draw()** function for the main program calls the **draw()** method of every tile during every small time interval, or *frame*. According to the prior code, if the tile is not active, then it will not be drawn. Let's test this.

> *Rule: Never write more than 20-30 lines of code without testing at least part of it.* That way you have a clearer idea where any problems you introduce may be.

A suitable test program to start with could be as follows:

```
def draw():
    global tiles
    for k in tiles:
        k.draw()

tiles = ()
red = (250, 0, 0)
for i in range (0, 12):
    tiles = tiles + (tile(i*30+15, 90, red, 15),)
```

which places some tiles on the screen in a row, passing a color and point value. This almost works, but the first tile is cut in half by the left boundary. If the initialization becomes

```
tiles = tiles + (tile(i*30+15, 90, red, 15),)
```

then a proper row of 12 red circles is drawn. Modifications will be made to this class once we see more clearly how it will be used.

12.3.2 Initial Coding for the Paddle

The paddle is represented as a rectangle on the screen, but its role in the game is much more profound: it is the only way the player has to participate in the game. The player types keys to control the position of the paddle so as to keep the ball from falling out of the area. The ball has to be drawn, as the tiles do, but it also must be moved (i.e., change the X position) in accordance with the player's wishes. The *paddle* class initially has a few basic operations:

```
class paddle:
    def __init__(self, x, y):
        self.x = x
        self.y = y
        self.speed = 3
        self.width = 90
        self.height = 10

def draw(self):
    pygame.draw.rect (screen, (self.color[0], self.
    color[1], self.color[2]), (self.x, self.y, self.width,
    self.height))

    def moveleft(self):
        if self.x <= self.speed:
           self.x = 0
        else:
            self.x = self.x - self.speed

    def moveright (self):
        if self.x > width-self.width-self.speed:
           self.x = width-self.width
        else:
            self.x = self.x + self.speed
```

When the right arrow key is pressed, a flag is set to **True**, and the paddle moves to the right (i.e., its x coordinate increases) each time interval, or frame. When the key is released, the flag is set to **False** and the movement stops as a result. Movement is accomplished by calling **moveleft()** and **moveright(),** and these functions enforce a limit on motion: the paddle cannot leave the play area. This is done within the class so that the outside code does not need to know anything about how the paddle is implemented. It is important to isolate details of the class implementation to the class only, so that modifications and debugging can be limited to the class itself.

The paddle is simply a rectangle, as far as the geometry is concerned, and presents a horizontal surface from which the ball will bounce. It is the only means by which the player can manipulate the game, so it is important to get the paddle operations and motion correct. Fortunately, moving a rectangle left and right is an easy thing to do.

12.3.3 Initial Coding for the Ball

The ball really does much of the actual work in the game. Yes, the bounces are controlled by the user through the paddle, but once the ball bounces off of the paddle, it has to behave properly and do the works of the game: destroying tiles. According to the standard class model of this program, the ball should have a **draw()** method that places it into its proper position on the screen. But the ball is moving, so its position has to be updated each frame. It also has to bounce off of the sides and top of the playing area, and the **draw()** method can make this happen. The essential code for doing this is as follows:

```
class ball():
    def __init__ (self, x, y):
        self.x = x
        self.y = y
        self.dx = 3
        self.dy = -4
        self.active = True
        self.color = (230, 0, 230)
        self.size = 9

def draw(self):
    if not self.active:
        return
    pygame.draw.circle(screen, (self.color[0],
                       self.color[1], self.color[2]),
                       (int(self.x), int(self.y)),
                       self.size // 2)
                       # Ball is a circle
    self.x = self.x + self.dx
    self.y = self.y + self.dy
    if (self.x <= self.size/2) or \
          (self.x >= width-self.size/4):
        self.dx = -self.dx
    if self.y <= self.size/2:
        self.dy = -self.dy
    elif self.dy >= height:
        self.active = False
```

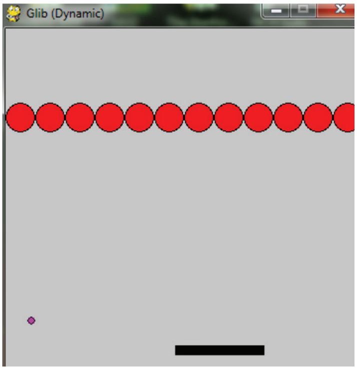


Figure 12.2
The basic elements of the game: ball, targets, and paddle.

This version only bounces off of the sides and top, and passes through the bottom.

12.3.4 Collecting the Classes

A next step is to test all three classes running together. This will ensure that there are no problems with variable, method, and function names, and that interactions between the classes are isolated. All three should work together, creating the correct visual impression on the screen. The code for the three classes was copied to one file for this test. The main program simply creates instances of each class as appropriate, really doing what the original test program did in each case:

```
red = (250, 0, 0)
print (red)
tiles = ()
for i in range (0, 12):
    tiles = tiles + (tile(i*30+15, 90, red, 15),)
f = True
p = paddle (130)
b = ball (300, 300)
```

The **draw()** function calls the **draw()** methods for each class instance and moves the paddle randomly as before:

```
def draw():     # 07-classes-01-20.py
    global tiles,p,f,b,movingleft,movingright
```

```
    screen.fill((200, 200, 200))
    # Tiles
    for k in tiles:
        k.draw()
# Paddle
    if movingleft:
        p.moveleft()
    elif movingright:
        p.moveright()
    p.draw()
# Ball
    b.draw()
```

The result was that all three classes functioned together the first time it was attempted. The game itself depends on collision, which will be implemented next, but at the very least the classes need to cooperate, or at least not interfere with each other. That's true at this point in the development.

12.3.5 Developing the Paddle

Placing the paddle under control of the user is the next step. When a key is pressed, then the paddle state changes, from still to moving, and vice versa when released. This is accomplished using the **keypressed()** and **keyreleased()** functions. They set or clear a flag, respectively, that causes the paddle to move by calling the **moveleft()** and **moveright()** methods. The flag **movingleft** results in a decrease in the paddle's x coordinate each time **draw()** is called; **movingright** does the same for the +x direction:

```
def keyPressed (k):
    global movingleft, movingright
    if k.key == pygame.K_LEFT:
        movingleft = True
    elif k.key == pygame.K_RIGHT:
        movingright = True

def keyReleased (k):
    global movingleft, movingright
    if k.key == pygame.K_LEFT:
        movingleft = False
    elif k.key == pygame.K_RIGHT:
        movingright = False
```

From the user's perspective, the paddle moves as long as the key is depressed. Inside of the global **draw()** function, the flags are tested at each iteration and the paddle is moved if necessary:

```
def draw():     # 07-classes-01-20.py
    global  … movingleft,movingright
      .  .  .
    if movingleft:
        p.moveleft()
    elif movingright:
        p.moveright()
    p.draw()
      .  .  .
```

The other thing the paddle has to do is serve as a bounce platform for the ball. A question surrounds the location of collision detection; is this the job of the *ball* or the *paddle*? It does make sense to perform most of this task in the *ball* class, because the ball is always in motion and is the thing that bounces. However, the *paddle* class can assist by providing necessary information. Of course, the paddle class can allow other classes to examine and modify its position and velocity, and thus perform collision testing, but if those data are to be hidden, the option is to have a method that tests whether a moving object might have collided with the paddle. The **y** position of the paddle is fixed and is stored in a global variable paddle, so that is not an issue. A method in paddle that returns True if the **x** coordinate passed to it lies between the start and end of the paddle is as follows:

```
def inpaddle(self, x):
    if x < self.x:
        return False
    if x > self.x + self.width:
        return False
    return True
```

The *ball* class can now determine whether it collides with the paddle by checking its own y coordinate against the paddle and by calling **inpaddle()** to see if the ball's **x** position lies within the paddle. If so, it should bounce. The method **hitspaddle()** in the ball class returns True if the ball hits the paddle:

```
def hitspaddle (self):      # 08classes-01-21.py
    if self.y<=paddleY+2 and self.y>=paddleY-2:
        if p.inpaddle(self.x):
            return True
    return False
```

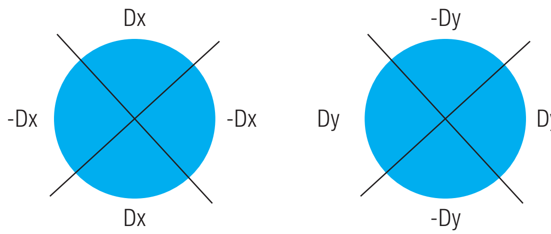
The most basic reaction to hitting the paddle is to change the direction of **dy** from down to up (**dy = -dy**).

12.3.6 Ball and Tile Collisions

The collision between a ball and a tile is more difficult to do correctly than any of the other collisions. Yes, determining whether a collision occurs is a similar process, and then points are collected and the tile is deactivated. It is the bounce of the ball that is hard to figure out. The ball may strike the tile at nearly any angle and at nearly any location on the circumference. This is not a problem in the original game, where the tiles were rectangular, because the ball was always bouncing off of a horizontal or vertical surface. Now there's some thinking to do.

The correct collision could be calculated, but would involve a certain amount of math. The specification of the problem does not say that mathematically correct bounces are required. This is a game design choice, perhaps not a programming choice. What does the game look like if a simple bounce is implemented? That could involve simply changing **dy** to **–dy**.

This version of the game turns out to be playable, but the ball always keeps the same x direction when it bounces. What would it look like if it bounced in roughly the right direction, and how difficult would that be? The direction of the bounce would be dictated by the impact location on the tile, as seen in Figure 12.3. This was determined after a few minutes with a pencil and paper, and it is intuitive rather than precise.



The value of Dx changes as the ball strikes one of the four parts or the circumstance.

The value of Dy changes as the ball strikes one of the four parts or the circumstance.

Figure 12.3
Different parts of the target, when colliding with the ball, generate different bounces.

We need to find where the ball hits the tile, determine which of the four parts of the tile this lies in, and then create the new **dx** and **dy** values for the ball. A key aspect of the solution being developed is to avoid too much math that has to be done by the program. Is this possible?

The first step is to find the impact point. We could use a little bit of analytic geometry, or we could approximate. The fact is that the ball is not moving very fast, and the exact coordinates of the impact point are not required. At the beginning of the current frame, the ball was at (x, y) and at the beginning of the next, it is at ($x + dx$, $y + dy$). A good estimate of the point of impact is the mean value of these two points, or ($x + dx/2$, $y + dy/2$).

Within which of the four regions defined in Figure 12.3 is the impact point? The regions are defined by lines at 45 degrees and -45 degrees. The **atan()** function will, when using screen coordinates, have the –dx points between -45 and +45 degrees. The –dy points, where the direction of Y motion changes, involve the remaining collisions. What needs to be done is to find the angle of the line from the center of the to the ball and then compare that to -45 … +45.

Here is an example method named **bounce()** that does exactly this.

```
# Return the distance squared between the two points
def distance2 (self, x0,y0, x1, y1):
    return (x0-x1)*(x0-x1) + (y0-y1)*(y0-y1)

def bounce (self, t):
    dd = t.size/2 + self.size/2     # Bounce occurs when the
                                    # distance
    dd = dd * dd                    # Between ball and tile <
                                    # radii squared
    collide = False
    if self.distance2 (self.x, self.y, t.x, t.y) >= dd and \
   self.distance2 (self.x+self.dx, self.y+self.dy, t.x, t.y) < dd:
        self.x = self.x + self.dx/2  # Estimated impact point on
                                     # circle
        self.y = self.y + self.dy/2
        collide = True
    elif self.distance2 (self.x, self.y, t.x, t.y) < dd:
        collide = True          # Ball is completely inside the time
    if not collide:
        return
```

```
# If the ball is inside the tile, back it out.
    while self.distance2 (self.x, self.y, t.x, t.y) < dd:
        self.x = self.x - self.dx*0.5
        self.y = self.y - self.dy*0.5
    if self.x != t.x:                    # Compute the ball-tile
                                         # angle
        a = atan ((self.y-t.x)/(self.x-t.y))
        a = a * 180./3.1415
    else:                                # If dx = 0 the tangent is
                                         # infinite
        a = 90.0
    if a >= -45.0 and a<=45.0:           # The x speed change
        self.dx = -self.dx
    else:
        self.dy = -self.dy               # The y speed changes
```

After testing the code, we include

```
# If the ball is inside the tile, back it out.
    while self.distance2 (self.x, self.y, t.x, t.y) < dd:
        self.x = self.x - self.dx*0.5
        self.y = self.y - self.dy*0.5
```

It was found that if the ball was too far inside the tile, then its motion was very odd; as it moved through the tile, it constantly changed direction because the program determined that it was always colliding.

12.3.7 Ball and Paddle Collisions

Let's examine the collision between the ball and the paddle. The paddle seems to be flat, and colliding with any location on the paddle should have the same result. What if the ball hits the paddle very near to one end? There is a corner, and maybe hitting too near to the corner would yield a different bounce. This was the case in the original games. If the ball struck the near edge of the paddle on the corner, it could actually bounce back in the original direction to a greater or lesser degree. This gives the player a greater degree of control, once they understand the situation. Otherwise, the game is pre-determined if the player merely places the paddle in the way of the ball. It will always bounce in exactly the same manner.

The proposed idea is to bounce at a different angle depending on where the ball strikes the paddle. We need to decide how near and how intense the effect will be. If the ball hits the paddle near the center, then it will bounce so that the incoming angle is the same as the outgoing angle. When it hits the near end of the paddle, it will bounce somewhat back in the incoming direction, and when it strikes the far end, the bounce angle will be a shallower bounce from the center.

Let's say that if the ball hits the first pixel on the paddle, it will bounce back in the original direction, meaning that **dx = -dx** and **dy = -dy**. A bounce from the center does not change **dx** but does set **dy = -dy**. If the relationship is linear across the paddle, the implication would be that striking the final pixel would set **dx = 2*dx** and **dy = -dy**. Striking any pixel in between would divide the change in dx by the number of pixels in the paddle, initially 90. If the ball hits pixel **n**, the result is as follows:

$$\text{delta} = 2*dx/90.0$$
$$dx = -dx + n*\text{delta}$$

A problem here is that the dx value decreases continuously until the ball is bouncing up and down. Perhaps the incoming angle should not be considered. The bounce angle of the ball could be completely dependent on where it hits the paddle and nothing else. If dx is -5 on the near end of the paddle and +5 on the far end, then,

$$dx = -5 + n*10.0/90.0$$

The code in the **draw()** method of the ball class is modified to read:

```
if self.hitspaddle():
    self.dy = -self.dy
    self.dx = -5 + (1./9.)*(self.x-p.x)
```

The user now has more control. The game does appear slow, though. In addition, there is only one ball. Once that is lost, the game is over.

12.3.8 Finishing the Game

What remains to be done is to implement multiple balls. Multiple balls are tricky because there are timing issues. When the ball disappears through the bottom of the play area, it should reappear someplace, and at a random place. It should not appear immediately, though, because the player needs some time to respond; let's say three seconds. Meanwhile, the screen must continue to be displayed. It's time to introduce states.

A *state* is a situation that can be described by a characteristic set of parameters. A state can be labeled with a simple number, but represents something complex. In this instance, specifically there will be a *play* state, in which the paddle can be moved and the ball can score points, and a *pause* state, which happens after a ball is lost. The **draw()** function is the place where each step of the program is performed at a high level, and so will be responsible for the management of states.

The current stage of the implementation has only the play state, and all of the code that manages that is in the **draw()** function already. Change the name of **draw()** to **state0()** and create a state variable **state** that can have values 0 or 1: *play* is 0, *pause* is 1. The new **draw()** function is now created:

```
def draw ():
    global playstate, pausestate
    if state == playstate:
        state0()
    elif state == pausestate:
        state1()
```

where

```
playstate = 0
pausestate = 1
```

The program should still be playable as it was before as long as **state == playstate**. What happens in the *pause* state? The controls of the paddle should be disabled, and no ball is drawn. The goal of the *pause* state is to allow some time for the user to get ready for the next ball, so some time is allowed to pass. Perhaps the player should be permitted to start the game again with a new ball when a key is pressed. This eliminates the need for a timer, which are generally to be avoided. The *pause* state is entered when the ball departs the field of play. The game remains in the *pause* state until the player presses a key, at which point a new ball is created and the game enters the *play* state.

Entering the *pause* state means modifying the code in the *ball* class a little. There is a line of code at the end of the **draw()** method of the *ball* class that looks like this:

```
elif self.dy >= height:
    self.active = False
```

This is where the class detects the ball leaving the play area. We need to add to this code:

```
if self.y >= height:                    # LEaves the play area?
    if balls_remaining>0:               # Yes. Balls left?
        state = pausestate              # Yes. Pause
        balls_remaining = balls_remaining-1
                                        # One less ball ...
    else:
        state = gameoverstate           # No. Game over
```

while, of course, making certain that the variables needed are listed as global. This did not do as was expected until it was noted that the condition should have been if **self.y >= height**. The comparison with **dy** was an error in the initial coding that had not been noticed. It also seems like the **active** variable in the *ball* class was not useful, so it was removed.

Now, in the **keyPressed()** function, we allow a key press to change from the pause to the play state. Any key will do:

```
if state = pausestate:
    resume()
```

The **resume()** function must do two things. First, it must change state back to *play*. Next it must reposition the ball to a new location.

```
def resume():
    global state, playstate
    b.x = randrange (30, width-30)
    b.y = 250
    state = playstate
```

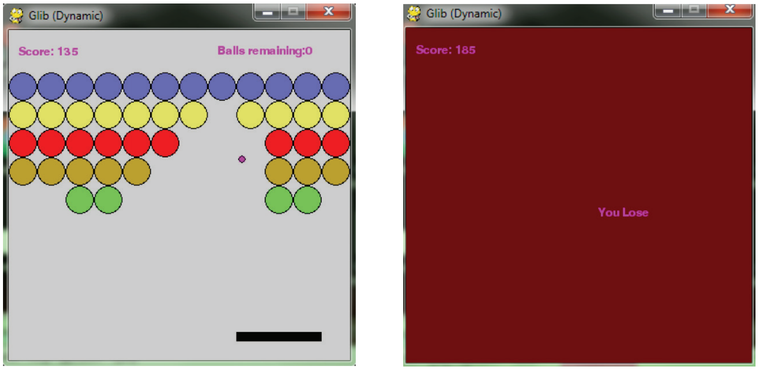
This works fine. The game is to only have a specified number of balls, though, and this number was to be displayed on the screen. When in the play state and a ball is lost, the count of remaining balls (**balls_remaining**) is decreased by one. If there are any balls remaining, then the pause state is entered. Otherwise, the game is over. Perhaps that should be a third state: *game over*.

The game-over state is entered when the ball leaves the play area and no balls are left (in the *ball* class **draw()** method). In the global **draw()** function, the third state determines if the game is won or lost and renders an appropriate screen:

```
. . .
if score >= maxscore:               # The gameover state. Win?
    screen.fill((0,230, 0))         # Yes
```

```
    text ("You Win", 200, 200)
else:
    screen.fill((200, 10, 10)) # Lose, there are btiles left.
    text ("You Lose", 200, 200)
    text ("Score: "+str(score), 10, 30)
```

Screen shots from the game in various states are shown in Figure 12.4 (14playble3.py).



(a) (b)

Figure 12.4
Screen shots from the game. (a) While play is going on. (b) The final screen; in this case, the player has lost.

12.4 RULES FOR PROGRAMMERS

The author of this book has collected a set of rules and laws that apply to writing code, based on his experience of having written tens of thousands of lines of code and 45 years as a programmer. There are over 250 of them, but not all apply to Python. For example, Python enforces indenting and has no begin-end symbols. The ones that do apply are as follows:

1. Use four-space indents and not tabs.
2. Place a comment in lieu of a declaration for all variables in languages where declarations are not permitted.
3. Declare numeric constants and provide a comment explaining them.
4. Rarely use a numeric constant in an expression; name and declare them.

5. Use variable names that refer to the use or meaning of the variable.
6. Make your code clean from the beginning, not after it works.
7. A non-working program is useless, no matter how well structured.
8. Write code that is as general as possible, even if that makes it longer.
9. If the code you write is general, then keep it and reuse it when appropriate.
10. Functions longer than 12 (not including declarations) lines are suspect.
11. Avoid recursion wherever possible.
12. Every procedure and function must have comments explaining function and use.
13. Write external documentation as you code—every procedure and function must have a description in that document.
14. Some documentation is for programmers, and some is for users. Distinguish.
15. Documentation for users must never be in the code.
16. Avoid using operating system calls.
17. Avoid using machine-dependent techniques.
18. Do use the programming language library functions.
19. Documentation for a procedure includes what other procedures are called.
20. Documentation for a procedure includes what procedures might call it.
21. When doing input: assume that the input file is wrong.
22. Your program should accept ANY input without crashing. Feed it an executable as a test.
23. Side effects are very bad. A proper function should return a value that depends only on its parameters. Exceptions do exist and should be documented.
24. Everything not defined is undefined.
25. Buffers and strings have fixed sizes. Know what they are and be constrained by them.
26. A handle is a pointer to a structure for an object; make certain that handles used are still valid.
27. Strings and buffers should not overlap in storage.

28. Contents of strings and buffers are undefined until written to.
29. Every variable that is declared is to be given a value before it is used.
30. Put some blank lines between method definitions.
31. Explain each declared variable in a comment.
32. Solve the problem requested, not the general case or subsets.
33. White space is one of the most effective comments.
34. Avoid global symbols where possible; use them properly where useful.
35. Avoid casts (type casting).
36. Round explicitly when rounding is needed.
37. Always check the error return codes.
38. Leave spaces around operators such as =, ==, and !=.
39. A method should have a clear, single, identifiable task.
40. A class should represent a clear, single, identifiable concept.
41. Do the comments first.
42. A function should have only one exit point.
43. Read the code.
44. Comments should be sentences.
45. A comment shouldn't re-state the obvious.
46. Comments should align.
47. Don't confuse familiarity with readability.
48. A function should be called more than once.
49. Code used more than once should be put into a function.
50. All code should be printable.
51. Don't write very long lines (no more than 80 characters).
52. The function name must agree with what the function does.
53. Format programs in a consistent manner.
54. Have a log.
55. Document all the principal data structures.
56. Don't print a message for a recoverable error—log it.
57. Don't use system-dependent functions for error messages.
58. You must always correctly attribute all code in the module header.

59. Provide cross references in the code to any documents relevant to the understanding of the code.
60. All errors should be listed together with an English description of what they mean.
61. An error message should tell the user the correct way to do it.
62. Comments should be clear and concise and avoid unnecessary wordiness.
63. Spelling counts.
64. Run your code through a spelling checker.
65. Function documentation includes the domain of valid inputs to the function.
66. Function documentation includes the range of valid outputs from the function.
67. Each file must start with a short description of the module contained in the file and a brief description of all exported functions.
68. Do not comment out old code—remove it.
69. Use a source code control system.
70. Comments should never be used to explain the language.
71. Don't put more than one statement on a line.
72. Never blindly make changes to code trying to remove an error.
73. Printing variable values in key places can help you find the location of a bug.
74. One compilation error can hide scores of others.
75. If you can't seem to solve a problem, then do something else.
76. Explain it to the duck. Get an inanimate object and explain your problem to it. This often solves it. (Wyvill)
77. Don't confuse ease of learning with ease of use.
78. A program should be written at least twice—throw away the first one.
79. Haste is not speed.
80. You can't measure productivity by volume.
81. Expect to spend more time in design and less in development
82. You can't program in isolation.
83. If an **if** ends in **return**, don't use **else**.

84. Avoid operator overloading.
85. Scores of compilation errors can sometimes be fixed with one character—start at the first one.
86. Programs that compile mostly still do not work.
87. Incrementally refine your code. Start with BEGIN-SOLVE-END, then refine SOLVE.
88. Draw diagrams of data and algorithms.
89. Use a symbolic debugger wherever possible.
90. Make certain that files have the correct name (and suffix!) when opening.
91. Never assign a value in a conditional expression.
92. If you can't say it in English, you can't say it in any programming language.
93. Don't move language idioms from one language to another.
94. Do no harm.
95. If the program is object oriented, design the objects first.
96. Don't write deeply nested code.
97. Multiple inheritance is evil. Avoid this sin.
98. Productivity can be measured in the number of keystrokes (sometimes).
99. Your code is not perfect. Not even close. Have no ego about it.
100. Variables are to be declared with the smallest possible scope.
101. The names of variables and functions should begin with a lowercase letter.
102. Collect your best working modules into a code library.
103. Isolate dirty code (e.g., code that accesses machine dependencies) into distinct and carefully annotated modules.
104. Anything you assume about the user will eventually be wrong.
105. Every time a rule is broken, this must be clearly documented.
106. Write code for the next programmer, not for the computer.
107. Your program should always degrade gracefully.
108. Don't surprise your user.
109. Involve users in the development process.
110. Most programs should run the same way and give the same results each time they are executed.

111. Most of your code will be checking for errors and potential errors.
112. Normal code and error handling code should be distinct.
113. Don't write very large modules.
114. Put the shortest clause of an if/else on top.
115. Have a library of error-reporting code and use it (be consistent).
116. Report errors in a way that they make sense.
117. Report errors in a way that allows them to be corrected.
118. Only fools think they can optimize code better than a good compiler.
119. Change the algorithm, not the code, to make things faster. A polynomial is a polynomial.
120. Copying and pasting is only for prototypes.
121. It's always your fault.
122. Know what the problem is before you start coding.
123. Don't re-invent the wheel.
124. Keep things as simple as possible.
125. Data structures, not algorithms, are central to programming. (Pike)
126. Learn from your mistakes.
127. Learn from the mistakes of others.
128. First make it work, then make it work faster.
129. We almost never need to make it faster.
130. First make it work, then make it work better.
131. Programmers don't get to make big design decisions—do what is asked, effectively.
132. Learn new languages and techniques when you can.
133. Never start a new project in a language you don't already know.
134. You can learn a new language effectively by coding something significant in it, just don't expect to sell the result.
135. You will always know only a subset of any given language.
136. The subset you know will not be the same as the subset your co-workers know.
137. Object orientation is not the only way to do things.
138. Object orientation is not always the best way to do things.
139. To create a decent object, one first needs to be a programmer.

140. You may be smarter than the previous programmer, but leave their code alone unless it is broken.
141. You probably are not smarter than the previous programmer, so leave their code alone unless it is broken.
142. Your program will never actually be complete. Live with it.
143. All functions have preconditions for their correct use.
144. Sometimes a function cannot tell whether its preconditions are true.
145. Computers have gigabytes of memory, mostly. Optimizing it is the last thing to do.
146. Compute important values in two different ways and compare them.
147. 0.1 * 10 is not equal to 1.
148. Adding manpower to a late software project makes it later.
149. It always takes longer than you expect.
150. If it can be null, it will be null.
151. Do not use catch and throw unless you know exactly what you are doing (be careful with exception handling).
152. Be clear about your intention. i=1-i is not the same as if(i==0) then i=1 else i=0.
153. Fancy algorithms are buggier than simple ones, and they're much harder to implement. (Pike)
154. The first 90% of the code takes 10% of the time. The remaining 10% takes the other 90% of the time.
155. All messages should be tagged.
156. Do not use FOR loops as time delays.
157. A user interface should not look like a computer program.
158. Decompose complex problems into smaller tasks.
159. Use the appropriate language for the job, when given a choice.
160. Know the size of the standard data types.
161. If you simultaneously hit two keys on the keyboard, the one that you do not want will appear on the screen.
162. Patterns are for the weak—it assumes you don't know what you are doing.
163. Don't assume precedence rules, especially when debugging—parenthesize.

164. Do not use ++ and --. Use code like i = i + 1.
165. It's hard to see where a program spends most of its time.
166. Fancy algorithms are slow when n is small, and n is usually small. (Pike)
167. Assume that things will go wrong.
168. Computers don't know any math.
169. Expect the impossible.
170. Test everything. Test often.
171. Do the simple bits first.
172. Don't fix what is not broken.
173. If it is not broken, then try to break it.
174. Don't draw conclusions based on names.
175. A carelessly planned project takes three times longer to complete than expected; a carefully planned project takes only twice as long.
176. Any system that depends on human reliability is unreliable.
177. The effort required to correct course increases geometrically with time.
178. Complex problems have simple, easy to understand, and wrong answers.
179. An expert is that person most surprised by the latest evidence to the contrary.
180. One man's error is another man's data.
181. Noise is something in data that you don't want. Someone does want it.

12.5 SUMMARY

There is no general agreement on how best to put together a good program. A good program is one that is functionally correct, readable, modifiable, reasonably efficient, and that solves a problem that someone needs solved. No two programmers will create the same program for a non-trivial problem. The program development strategy discussed in this chapter is called *iterative refinement*, and it is nearly independent of language or philosophy.

There is no single process that is best for writing programs. Some people only use object-oriented code, but a problem with teaching that way is that a class contains traditional, procedure-oriented code. To make a class, one must first know how to write a program.

The idea behind *top-down* programming is that the higher levels of abstraction are described first. A description of what the entire program is to do is written in a kind-of English/computer hybrid language (*pseudocode*), and this description involves making calls to functions that have not yet been written but whose function is known—these functions are called *stubs*. The first step is to sketch the actions of the program as a whole, then to expand each step that is not well-defined into a detailed method that has no ambiguity. Compile and test the program as frequently as possible so that errors can be identified while it is still easy to see where they are.

The key to object-oriented design is identifying the best objects to be implemented. The rest of the program will take a logical shape depending on the classes that it uses. Try to isolate the details of the class from the outside. Always be willing to re-think a choice and re-write code as a consequence.

Exercises

1. Add sound to the game. When the ball collides with an object, a sound effect should play.
2. Consider how hyphenation might be added to Pyroff. How would it be decided to hyphenate a word, and where would the new code be placed? In other words, sketch a solution.
3. In some versions of Breakout-style games, certain of the tiles or targets have special properties. For example, sometimes hitting a special target will result in the ball speeding up or slowing down, will have an extra point value, or will change the size of the paddle. Modify the game so that some of the targets speed up the ball and some others slow it down.
4. The Pyroff system can turn the right adjustment off, but not on. This seems like a flaw. Add a new command, ".ra" that will turn the right adjustment on.
5. Most word processors allow for a header and a footer, some space and possibly some text at the beginning and end, respectively, of every page. Design a command ".he" that at the least allows for empty space at the beginning of a page, and a corresponding command ".fo" that allows for some lines at the end of a page.

6. Which three of the *Rules for Programmers* do you think make the greatest difference in the code? Which three affect code the least? Are there any that you don't understand?

Notes and Other Resources

Bouncing a ball off of a wall: *https://sinepost.wordpress.com/2012/08/19/bouncing-off-the-walls/*

1. Jon Bentley. (1999). *Programming Pearls, 2nd ed.,* Addison-Wesley Professional, ISBN-13: 978-0201657883.
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6. R. Rhoad, G. Milauskas, and R. Whipple. (1984). ***Geometry for Enjoyment and Challenge, rev. ed.***, Evanston, IL, McDougal, Littell & Company.
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CHAPTER 13

COMMUNICATING WITH THE OUTSIDE WORLD

In this chapter

Python can read data from the keyboard and print information on the screen. It can display graphics, audio, and video, allow mouse (and touch) interactions, and read and write data to and from files. That's a lot of communication, but it all happens on one computer—the one on which the program is running. In the age of high-speed Internet, social media, podcasts, blogs, and wikis, this is not enough.

Can computers communicate with another one? Of course. Can a program send email? Yes, that's what a mail program like *Thunderbird* or *Outlook* does. Can a program be written that reads tweets as they are sent? Yes. However, all these things are done according to someone else's rules. The first email was sent in 1971 on a private network named *Arpanet*. It sent mail between distinct computers, rather than sending messages between users on a specific machine. In 1972, Unix email was made available, and it was networked in 1978.

The sender and receiver had to agree on how to encode and decode a message, and how to access it from the network. To send mail between different computers always requires a standard, a scheme that is agreed upon by implementers of the system. Otherwise, mail can only be sent between UNIX systems, or Windows, or iOS. email, to be practical, needs to be flexible. It needs to be ubiquitous, and so all need to agree on a standard for how email can be sent and received. A standard was eventually agreed on, called the *Simple Mail Transfer Protocol* (SMTP), and it was established in 1982.

This was seven years before the World Wide Web, so email really represents the first practical way to communicate between computers over a long distance. FTP happened at about the same time. The enabling technology for the Web, TCP/IP, came next. All of these developments in networking and software combined to create the modern interconnected society, but all are based on a collection of rules that software must agree to (*protocols*) if they are to make use of the network infrastructure. This is an example of *design by contract*, in which designers create formal specifications for components and using those involves a kind-of contract or agreement between programmers developing client software and those who built the modules and designed the protocols.

There are high-level programs that provide a good user interface to the Internet and that implement these protocols beneath their visual presentation. When using Python, a collection of modules is used that handles the very low-level details, but the interface to the programmer exposes the protocol. Some of these modules are provided in a standard Python installation (*smtplib* and *email*), and some are not (*MPI* and *tweepy*), and will have to be installed before the code in this chapter will run.

When communicating with another machine, a key issue is that of *authentication*. Almost all protocols require that a connection be formed between the two computers, using some kind of identification of those machines, such as their IP address. Then the one initializing the connection must prove that it has permission to do what it is about to do. This resembles logging in, and it involves a user identification and a password of some type. Once the user has been identified, there is an exchange of messages that tell the remote computer what is desired of it and that allow information to be returned to the caller. This process is nearly universal, but takes somewhat different forms on different systems.

13.1 EMAIL

Email is a good example of a *client-server* system, and one that gets used millions of times each minute. The email program on a PC is the client, and allows a user to enter text messages, specify destinations, attach images, and all of the features expected by such a program. This client packages the email message (data) according to the *Simple Message Transfer Protocol* (SMTP) and sends that to another computer on the Internet, the email server. An email user must have an account on the server for this to work so they can be identified and the user can receive replies. The process is as follows: log into the email server, then send the SMTP message to the email server program on that server. Thus, the client side of the contract is to create a properly formatted message, to log into the server properly, and pass the message to it.

Now the server does the work. Given the destination of the message, it searches for the server that is connected to that destination. For example, given the address xyz@gmail.com, the server for gmail.com is located. Then the email message is sent across the network to that server. The server software at that end reads the message and places it into the mailbox, which is really just a directory on a disk drive connected to the server, for the specified use **xyz**. The mail message is essentially a text file at this point.

This description is simplified but essentially accurate, and describes what has to be done by a program that is supposed to send an email message. The Python module that permits the sending of email implements the protocol and offers the programmer ways to specify the parameters, like the destination and the message. The interface is implemented as a set of functions. The library needed for this is *smtplib*, a part of the standard Python system.

Example: Sending an email

Sending an email message starts with establishing a connection between the client computer and the user's mail server, the one on which they have an account (user name and password). For the purposes here, a Gmail (Google) server is used. The email accounts in the example are also Gmail ones, and these can be had for free from Google.

The program must declare *smtplib* as an imported module. The sending address and the receiving address are the same in this example, but this is just a test. Normally, this will not be the situation. The email address is the user ID for Gmail authentication and the password is defined by the user. These are all strings.

```
import smtplib

LOGIN = yourloginID      # Login User ID for Gmail, string
PASSWD = yourpassword    # Login password for Gmail, string
sndr = pythontextbook@gmail.com      # Sender's email address
rcvr = pythontextbook@gmail.com      # Receiver's email ad-
dress
```

Part of the SMTP scheme is a syntax for email messages. There is a header at the beginning that specifies the sender, receiver, and subject of the message. These are used to format the message, not to route it—the receiver address is specified later. A simple such message looks like this:

```
From: user_me@gmail.com
To: user_you@gmail.com
Subject: Just a message
```

A string must be constructed that contains this information:

```
msgt = "From: user_me@gmail.com\n"
msgt = msgt + "To: user_you@gmail.com\n"
msgt = msgt + "Subject: Just a message\n"
msgt = msgt + "\n"
```

Now the body of the message is attached to this string. This is the part of the email that is important to the sender:

```
msgt = msgt + "Attention: This message was sent by Python!\n"
```

The string variable **msgt** now holds the whole message. This message is in the format defined by the Multipurpose Internet Mail Extensions (MIME) standard. The next step for the program is to try to establish a connection with the sender's email server. For this, the *smtp* module is needed, specifically the **SMTP()** function. It is called, passing the name of the user's email server as a parameter, and it returns a variable that references that server. In this example, that variable is named server:

```
server = smtplib.SMTP('smtp.gmail.com')
```

If it is not possible to connect to the server for some reason, then an error will occur. It is therefore a good idea to place this in a try-except block:

```
try:
    server = smtplib.SMTP('smtp.gmail.com')
except:
    print ("Error occurred. Can't connect")
else:
```

Now comes the complexity that Gmail and some other servers introduce. What happened after the call to **smtplib.SMTP()** is that a communications session has been opened up. There is now an active connection between the client computer and the server at *smtp.gmail.com*. Some servers demand a level of security that ensures that other parties cannot modify or even read the message. This is accomplished using a protocol named *Transport Layer Security* (TLS), the details of which are not completely relevant because the modules take care of it. However, to send data to *smtp.gmail.com*, the server must be told to begin using TLS:

```
server.starttls()
```

Now the user must be authenticated using their ID and password:

```
server.login(LOGIN,PASSWD)
```

Only now can a message be sent, and only if the login ID and password are correct. The sender is the string **sndr**, the recipient is **rcvr**, and the message is **msgt**:

```
server.sendmail(sndr, rcvr, msgt)
```

Now that the message has been sent, it is time to close the session. Logging off of the server is done as follows:

```
server.quit()
```

This program sends one email, but it can be easily modified to send many emails, one after the other. It can be modified to read the message from the keyboard, or perform any of the functions of a typical email-sending program (Exercise 1).

The module email can be invoked to format the message in MIME form. The function **MIMEText(s)** converts the message string **s** into an internal form, which is a MIME message. Fields like the subject and sender can be added to the message, and then it is sent as was done before. For example,

```
import smtplib
from email.mime.text import MIMEText

LOGIN = yourloginID
PASSWD = yourpassword

fp = open ("message.txt", "r")  # Read the message
                                # from a file
mtest = fp.read()
# Or: simply use a string
#mtest = "A message from Python: Merry Christmas."
fp.close()

msg = MIMEText (mtest)                # Create a MIME string
sndr = pythontextbook@gmail.com       # Sender's email
rcvr = pythontextbook@gmail.com       # Recipient's email
msg['Subject'] = 'Mail from Python'   # Add Subject to the
message
msg['From'] = sndr                   # Add sender to the message
msg['To'] = rcvr                     # Add recipent to the
                                     # message

# Send the message using Google's SMTP server, as before
s = smtplib.SMTP('smtp.gmail.com')   # localhost could work
s.starttls()
s.login (LOGIN, PASSWD)
s.send_message(msg)
s.quit()
```

Using **MIMEText()** to create the message avoids having to format it correctly using basic string operations.

Construct a MIME formatted message from the subject, sender, receipient, and body text.	Connect with the mail server `mbox = imaplib.IMAP4 _ SSL(imap.gmail.com)`
↓	↓
Connect with the mail server. `server = smtplib.SMTP('smtp.gmail.com')`	Identify and authenticate the user on the server. `mbox = login(USER, PASSWORD)`
↓	↓
Make the connection comply with TLS, if necessary	Select an inbox/email folder `env, data = mbox.select("Inbox")`
↓	↓
Identify and authenticate the user on the server. `server.login(LOGIN, PASSWD)`	Read the Mailbox `env, data = m.search(None, "ALL")`
↓	↓
Send the Email message to the server, identifying the sender and receipient `server.sendmail(sndr, rcvr, msgt)`	Fetch Messages `env, data = m.fetch(num, '(RFC822)')`
↓	↓
Close the connection	Log Out/Close
Process for sending an Email	Process for reading Email

Figure 13.1
The procedure for sending an email using Python.

13.1.1 Reading email

Reading email is more complicated than writing it. The content of an email is often a surprise, and so a reader must be prepared to parse anything that might be sent. There can be multiple mailboxes: which mailbox will be looked at? There are usually many messages in a mailbox: how can they be distinguished? In addition, the protocol for retrieving mail from a server is different from that used to send it. There are two competing protocols: POP and IMAP.

The *Post Office Protocol* (POP) is the older of the two schemes, although it has been updated a few times. It certainly allows the basic requirements of a mail reader, which is to download and delete a message in a remote mailbox (i.e., on the server). The *Internet Message Access Protocol* (IMAP) is intended for use by many email clients, and so messages tend not to be deleted until that is requested.

When setting up an email client, one of these protocols usually has to be specified, and then it will be used from then on. The example here uses IMAP.

13.1.2 Example: Display the Subject Headers for Emails in the Inbox

An outline for the process of reading email is sketched on the right side of Figure 13.1. Reading email uses a different module that was used to send email: *imaplib*, for reading from an IMAP server. The function names are different from those in *smtplib*, but the purpose of some of them is the same. The first three steps in reading email are as follows:

```
import imaplib
server = 'imap.gmail.com'           # Gmail's IMAP server
USER = pythontextbook@gmail.com     # User ID
PASSWORD = "password"               # Mask this password
EMAIL_FOLDER = "Inbox"

mbox = imaplib.IMAP4_SSL(server)    # Connect to the server
mbox.login(USER, PASSWORD)          # Authenticate (log in)
```

The next step is to select a mailbox to read. Each has a name, and is really just a directory someplace. The variable **mbox** is a class instance of a class named *imaplib.IMAP4_SSL*, the details of which can be found in many places, including the Internet. It has a method named **select()** that allows the examination of a mailbox, given its name (a string). The string is a variable named EMAIL_FOLDER, which contains "Inbox," and the call to **select()** that essentially opens the inbox is

```
z = mbox.select(EMAIL_FOLDER)
```

The return value is a tuple. The first element indicates success or failure, and if z[0] contains the string "OK," then the mailbox is open. The usual alternative is "NO." The second element of the tuple indicates how many messages there are, but it is in an odd format. If there are 2 messages, as in the example, this string is *b'2'*; if there were 3 messages it would be *b'3'*; and so on. These are called message sequence numbers.

Having opened the mailbox, the next step is to read it and extract the messages. The protocol requires that the mailbox be searched for the messages that are wanted. The *imaplib.IMAP4_SSL* class offers the **search()** method for this, the simplest form being

```
mbox.search(None, "ALL")
```

which returns all of the messages in the mailbox. IMAP provides search functionality, and all this method does is connect to it, which is why it seems awkward to use. The first parameter specifies a character set, and **None** allows it to default to a general value. The second parameter specifies a search criterion as a string. There are dozens of parameters that can be used here and the documentation for IMAP should be examined in detail for solutions to specific problems. However, some of the more useful tags include

ANSWERED: Messages that have been answered

BCC <string>: Messages with a specific string in the BCC field

BEFORE <date>: Messages whose date (not time) is earlier than the specified one

HEADER <field-name> <string>: A specified field in the header contains the string

SUBJECT <string>: Messages that contain the specified string in the SUBJECT field

TO <string>: Messages that contain the specified string in the TO field

UNSEEN: Messages that do not have the \Seen flag set

A call to **search()** that looks for the text "Python" in the subject line is

```
mbox.search(None, "SUBJECT Python")
```

The **search()** function returns a tuple again, where the first component is a status string (i.e., "OK," "NO," and "BAD") and the second is a list of messages satisfying the search criteria in the same format as before. If the second message if the only match, this string will be **b'2.'** If the first three match it will be **b'1 2 3.'**

Finally, the messages are read, or *fetched*. The *imaplib.IMAP4_SSL* class has a **fetch()** method to do this, and it again takes some odd parameters. What a programmer thinks of the interface or the API or, in other words, the *contract*, is not important. What must be done is to satisfy the requirements and accept the data as it is offered. The **fetch()** method accepts two parameters: the first is the indication of which message is desired. The first message is *b'1'*, the second is *b'2'*, and so on. The second parameter is an indicator of what it is that should be returned. The header? If so, pass (RFC822.HEADER) as the parameter. Why?

Because they ask for it. RFC822 is the name of a protocol. If the email body is wanted, then pass (RFC822.TEXT). A short list of possibilities is

RFC822	- Everything
RFC822.HEADER	- No body, header only
RFC822.TEXT	- Body only
RFC822.SIZE	- Message size
UID	- Message identifier

Multiple of these specifiers can be passed. For example,

```
mbox.fetch(num, '(UID RFC822.TEXT RFC822.HEADER)')
```

returns a tuple having three parts: the ID, the body, and the header. The header tends to be exceptionally long, 40 lines or so. For this example, the only part of the header that is interesting is the "Subject" part. Fields in the header are separated by the characters "\r\n," so they are easy to extract in a call to split(). Eliminating the header data for a moment, the call

```
(env, data) = mbox.fetch(num, '(UID RFC822.TEXT)')
```

results in a tuple that has an "envelope" that should indicate "OK" (the **env** variable). The data part is a string that contains the UID and the text body of the message. For example,

```
[(b'2 (UID 22 RFC822.TEXT {718}', b"Got a collection of old
45's for sale. Contact me.\r\n\r\n-- \r\n"), b')']
```

This says that this is message 2 and shows the text of that message.

This example is supposed to print all of the subject headers in this mailbox. The call to **fetch()** should extract the header only:

```
(env, data) = mbox.fetch(num, '(RFC822.HEADER)')
```

The details of IMAP are complex enough that it is easy to forget what the original task was, which was to print the subject lines from the messages in the mailbox. All of the relevant methods have been described and completing the program is possible. The entire program is as follows:

```
import imaplib

server = 'imap.gmail.com'           # IMAP Server
USER = "pythontextbook@gmail.com"   # USER ID
```

```
PASSWORD = ""                          # Mask this password
EMAIL_FOLDER = "Inbox"                 # Which mailbox?

mbox = imaplib.IMAP4_SSL(server)       # Connect
mbox.login(USER, PASSWORD)             # Authenticate

env, data = mbox.select(EMAIL_FOLDER)  # Select the mailbox
if env == 'OK':                        # Did it work?
    print ("Printing subject headers: ", EMAIL_FOLDER)

    env, data = mbox.search(None, "ALL")  # Select the
                                          # messages wanted.
    if env != 'OK':                       # Are there any?
        print ("No messages.", env)       # Nope.
        exit()

    for num in data[0].split():      # For each selected
                                     # message b'1 2 3 ...'
        (env, data) = mbox.fetch(num, '(RFC822.HEADER)')
                                                  # Read it
        if env != 'OK':
            print ("ERROR getting message", num, ", ", env)
            break
        s = str(data[0][1])      # Look for the string
                                 # "Subject" in the header
        k = s.find("Subject")
        if (k>=0):               # Found it?
            s =  s[k:]           # Extract the string
                                 # to the next '\r'
            k = s.find('\\r')
            s = s[:k]
            print (s)            # And print it.
    mbox.close()
else:
    print ("No such mailbox as ", EMAIL_FOLDER)
mbox.logout()
```

The typical output would be as follows:

Printing subject headers: Inbox
Subject: Contents of Chapter 13
Subject: 45 RPM
Subject: another email

The point of this section was to demonstrate how a Python program, or any program for that matter, must comply with external specifications when interfacing with sophisticated software systems, and to introduce the concept of a protocol, a contract between developers. A program that can send email is useful by itself.

13.2 FTP

The File Transfer Protocol (FTP) is used to exchange files between computers on a network. It provides the same sort of interface to data on a distance computer as would be expected from a file system on a desktop. It can copy a file in either direction, but can also change directories, list the directory contents, and perform other useful operations. This again presumes that the rules set up by the FTP interface are followed.

Having just seen the communication requirements for sending and receiving email, it should be possible to predict the way that FTP operates. A connection has to be made to a remote computer, and some form of authentication takes place. The client (the program that established the connection) now send a set of commands to the server, which reads and processes them. Then, finally, the client terminates the connection.

The commands that can be processed by an FTP server include listing the contents of the directory (LIST), changing the working directory (CWD), retrieving a file (RETR), and sending or storing a file (STOR). These are sent across the network as strings and represent raw FTP commands, and take place at a low level of abstraction in the system. Higher level commands are implemented as specific methods in the **FTP** class of *ftplib*. For example, there is a command named PWD that displays the name of the current remote directory. FTP offers a function that sends this command:

```
FTP.pwd()
```

Doing the same thing by sending the command directly uses the **sendcmd()** method of FTP, and it passes the command as a string:

```
ftp.sendcmd("PWD")
```

There is a difference to the programmer. The **pwd()** method returns the string that represents the directory, whereas when the text command is sent, the return value is the string that the FTP system returned, which is something like

257 “/” is the current directory

13.2.1 Example: Download and Display the README File from an FTP Site

The site chosen for the example belongs to NASA, but any ftp site will work. The connection and authentication steps are as follows:

```
from ftplib import FTP

ftp = FTP("ftp.hq.nasa.gov")  # Please don't always use NASA
ftp.login()                   # Select a different site.
```

The login step is interesting because there are no parameters given. This is an *anonymous* FTP connection, which is common for sites that offer things for download. The default login when using the login() method is a user ID of "anonymous" and a password, if one is requested, of "anonymous." It is also possible to specify an ID and password if the user has them:

```
ftp.login("myuserid", "mypassword")
```

The **login()** function returns the site's welcome message, which is a string that can be ignored.

The example is supposed to download the file named README and display it. The method **retrlines()** can do this, because it is a text file. If it were a binary file, like an MP3 or JPG file, then the **retrbinary()** method would be used instead. The first parameter to **retrlines()** is a command. To retrieve a file the command is the keyword **RETR** followed by the file name. The simplest version is

```
ftp.retrlines('RETR README')
```

which displays the text from the file on the screen. That's what was wanted, but the method can do more. If a function name is passed as the second parameter, then that function is called for with every line of text, and will pass that line as a parameter. To illustrate this, consider a simple function that takes a string and prints each line, looking for "\\n" characters. The function is

```
def myprint (ss):
    s = str(ss)  # Sometimes the parameter ss is type byte.
     x = s.split("\\n")
     for i in range (0, len(x)):
         print (x[i])
```

A call to **retrlines()** could be as follows:

```
ftp.retrlines('RETR README', myprint)
```

or even

```
ftp.retrlines('RETR README', print)
```

to use the standard **print()** function. Of course, any function that takes a string parameter could be passed. To save the README file as a local file, for example,

```
ftp.retrlines('RETR README', open('README', 'w').write)
```

writes the file to a local one named README, but it lacks the end-of-line characters.

Binary files use **retrbinary()**, and it has the same form as **retrlines()**. However, the second parameter, the function, must be passed, because binary files cannot be sent to the screen. Downloading and saving an image file might be done as follows:

```
ftp.retrbinary('RETR  orion.jpg,  open('orion.jpg,  'wb').
write)
```

The session would end by logging out:

```
ftp.quit()
```

Uploading a file, that is moving a file from a desktop to a site on the Internet, used the method **storlines()** for text and **storbinary()** for binary files. For example,

```
f = open ("message.txt", "rb")
ftp.storlines ("STOR message.txt", f)
```

The method copies lines from the local file to the remote one. The file to be copied is open in "rb" mode. For a binary example, assume there is an image:

```
f = open ("image.jpg", "rb")
ftp.storbinary ("STOR image.jpg", f)
session.storbinary('STOR kitten.jpg', file)  # send the file
```

13.3 COMMUNICATION BETWEEN PROCESSES

Underneath the FTP and email protocols, which allow interfaces to applications, lies a communications layer, the programs that actually send bytes between computers or between programs on the same computer. It is conducted very much like a conversation. One person, the client, initiates the conversation ("Hi there!"). The other (the server) responds ("Hello. Nice to see you."). Now, it is the client's turn again. They take turns sending and accepting messages until one says "goodbye." These messages might contain email, or FTP data, or TV programs. This layer does not care what the data is, its job is to deliver it.

Data are delivered in *packets*, each containing a certain amount. In order for the client to deliver the data, there must be a server willing to connect to it. The client needs to know the address of a server, just as an FTP address or email destination was required before, but now all that is needed is the host name and a *port number*. A port is really a logical construction, something akin to an element of a list. If two programs agree to share data by having one of them place it in location 50001 of a list and the other one read it from there, it gives an approximate idea of what a port is. Some port numbers are assigned and should not be used for anything else; FTP and email have assigned ports. Others are available for use, and any two processes can agree to use one.

A module named socket, based on the inter-process communication scheme on UNIX of the same name, is used with Python to send messages back and forth. To create an example, two computers should be used, one being the client and one the server, and the IP address of the server is required, too.

13.3.1 Example: A Server That Calculates Squares

The client opens a communications link (socket) to the server, which has a known IP address. The server engages in a short handshake (exchange of strings), and then expects to receive a number for the client. The client sends an integer, the server receives it, squares it, and sends back the answer. This simple exchange is really the basis for all communications between computers: one machine sends information, the other receives it, processes it, and returns a reply based on the data it received.

The *client* begins the conversation. It creates a connection, a socket, to the server using the **socket**() function of the **socket** module. Protocols must be specified, and the most common ones are used:

```
import socket

HOST = '19*.***.*.***'  # The remote host
PORT = 50007            # The same port as used by the server
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.connect((HOST, PORT))
```

Port 50007 is used because nothing else is using it. Now the client starts the conversation, just as it appears at the beginning of this section:

```
s.send(b'Hi there!')
```

The **send()** function sends the message passed as a parameter. The string (as *bytes*) is transmitted to the server through the variable **s**, which represents the server. The client now waits for the confirmation string from the server, which should be "Hello. Nice to see you." The client calls:

```
data = s.recv(1024)
```

which waits for a response from the server. This response is 1024 bytes long at most, and it waits only for a short time, at which point it gives up and an error is reported. When this client gets the response, it proceeds to send numbers to the server. They are converted into the *bytes* type before transmission. In this example, it simply loops through 100 consecutive integers:

```
for i in range (0, 100):
    data = str(i).encode()
    s.send (data)
```

After sending to the server, it waits for the answer. Actually, that's a part of the receive function:

```
data = s.recv(1024)
```

after 100 integers, the loop ends and the connection is closed:

```
s.close()
```

The *server* is always listening. It creates a socket on a particular port so that the operating system knows something is possible there, but because the server cannot predict when a client will connect or what client it will be it simply listens for a connection, by calling a function named **listen()**:

```
import socket
from random import *

HOST = ''    # A null string is correct here.
PORT = 50007
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.bind ((HOST, PORT))
s.listen()
```

AF_INET and SOCK_STREAM are constants that tell the system which protocols are being used. These are the most common, but see the documentation for others. The **bind()** and the **listen()** functions are new. Associating this connection with a specific port is done using **bind().** The tuple (HOST, PORT) says to connect this host to this port. The empty string for HOST implies *this* computer. The **listen()** call starts the server process, *this* program, accepting connections when asked. A process connecting on the port that was specified in *bind()* will now result in this process, the server, being notified. When a connection request occurs, the server must accept it before doing any input or output:

```
conn, addr = s.accept()
```

In the tuple **(conn, addr)** that is returned, **conn** represents the connection, like a file descriptor returned from **open()**, and it is used to send and receive data. **addr** is the address of the sender, the client, and it is a string. If the **addr** were printed,

```
print ("Connected to ", addr)
```

it would look like an IP address:

```
Connected to 423.121.12.211
```

Now, the server can receive data across the connection, and does so by calling **recv()**:

```
data = conn.recv(1024)
print ("Server heard '", data, "'")
```

The parameter 1024 specifies the size of the buffer, or the maximum number of bytes that can be received in one call. The variable **data** is of type *bytes*, just as the parameter to **send()** was in the client. The client was the first to send, and it sent the message "Hi there!" That should be the value of data now, if it has been received properly. The response from the server should be "Hello, nice to see you."

```
conn.send (b'Hello. Nice to see you.')
```

The same connection is used for sending and receiving.

Now the real data gets exchanged. The server accepts integers, sent as *bytes*. It squares them and transmits the answer back.

```
while True:
    data = conn.recv(1024)          # Read the incoming data
```

```
if data:
    i = int(data)                   # Convert it to integer
    print ("Received ", i)
    data = str(i*i).encode()        # Square it and convert
                                    # to bytes
    conn.send (data)                # Send to the client
```

The server can tell when the connection is closed by the client, but it is also polite to say "goodbye" somehow, perhaps by sending a particular code. If the loop ever terminates, the server should close the connection:

```
conn.close()
```

This is a pretty good example of a data exchange and a contract, because there are specified requirements for each side of this conversation that will result in success if done correctly and failure if messed up. Failure is sometimes indicated by an error message, often a *timeout*, where the client or server was expecting something that never arrived. In other cases, failure is not formally indicated at all; the program simply "hangs" there and does nothing. If at any time, both processes are trying to receive data, then the program will fail.

Figure 13.2 shows the communication between the client and the server as a diagram. If the client and the server are at any time both trying to accept data from the connection, then the program will fail. In the diagram, all data trans-

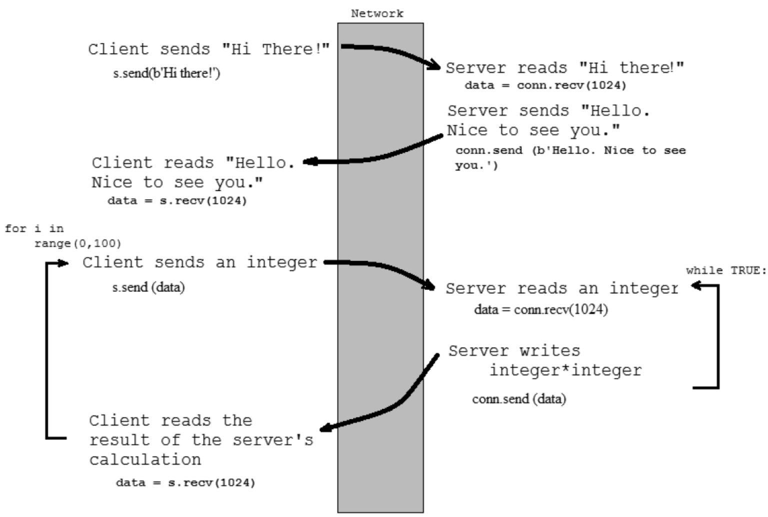

Figure 13.2
Typical communication between the client and the server processes.

fers are transmit-accept pairs between the two processes and as read-write pairs within the server and write-read pairs within the client.

The FTP protocol can now be seen as a socket connection, wherein the client sends strings (commands) to the server, which parses them, carries out the request, and then sends an acknowledgement back.

```
# The client
import socket

# The remote host
HOST = '19*.***.*.***'
# The same port used by
# the server
PORT = 50007

s = socket.socket(socket.
                  AF_INET,\
        socket.SOCK_STREAM)
s.connect((HOST, PORT))
s.send(b'Hi there!')
data = s.recv(1024)
for i in range (0, 100):
    data = str(i).encode()
    s.send (data)
    data = s.recv(1024)
s.close()
```

```
# The server
import socket

HOST = '' # A null string
          # is ok here.
PORT = 50007
s = socket.socket(socket.
                  AF_INET, \
      socket.SOCK_STREAM)
s.bind ((HOST, PORT))
s.listen()
conn, addr = s.accept()
data = conn.recv(1024)
print ("Server heard
               '", data, "'")
conn.send (b'Hello. Nice to
             see you.')
while True:
# Read the incoming data
    data = conn.recv(1024)
    if data:
# Convert it to integer
        i = int(data)
       print ("Received ", i)
# Square it and convert to
# bytes
         data = str(i*i).en-
code()
# Send to the client
        conn.send (data)
   conn.close()
```

13.4 TWITTER

Twitter is a social media service that allows its users to send short (140 character) messages out to its subscribed listeners. From its beginning in 2006, Twitter has grown to the point where it handles hundreds of millions of messages (*tweets*) per day from their 302 million active users. It differs from email in that it broadcasts messages, and the recipients are self-selected.

The messages are entered by Twitter users, each of whom has an account. All messages become part of a *stream*, and the ones that a particular user wants to see are pulled from that stream and placed on the user's *feed*. It is, however, possible to see the feed and examine messages as they are sent, collecting data or identifying patterns. Twitter allows access to the stream, but when using Python, it requires the use of a module that must be downloaded and installed. That module is called *tweepy*.

A warning: setting up the authentication so that the Twitter stream can be accessed is not simple. A Twitter account is needed, an application has to be registered, and the app must be specified as being able to read, write, and direct messages. Twitter creates a unique set of keys that must be used for the authentication: the consumer key and consumer secret key, then the access token and access secret token.

A tweet is limited to 140 characters, but that only considers content. The amount of data sent in a tweet is substantially larger than that, 6000 bytes or more. That's due to the large amount of metadata, or descriptive information, in a tweet. Most people never see that, but a program that reads tweets and sifts them for information will have to deal with it. The twitter interface returns tweet data in *JSON* format (JavaScript Object Notation), which is a standard for exchanging data, similar in purpose to XML. This format has to be parsed, but a second Python module named *json* will do that so no further discussion of JSON will be necessary.

13.4.1 Example: Connect to the Twitter Stream and Print Specific Messages

This program examines the twitter feed and prints messages that have the term "Star Trek" in them. It is useful to see that once again, authentication is one of the first things to do. In the case of tweepy, an object is created, passing the authentication strings.

```
import tweepy
import json
```

```
# Authentication details from dev.twitter.com
consumer_key = 'get your own'
consumer_secret = 'get your own'
access_token = 'get your own '
access_token_secret = ''get your own '

authentication = tweepy.OAuthHandler(consumer_key, consum-
er_secret)
authentication.set_access_token(access_token,
                                 access_token_secret)
```

Now something different is needed. Tweepy wants to have an object passed to it that is a subclass of one that it defines, *StreamListener*. As a part of the deal that is made with tweepy, the class must have a method named **on_data()** and another named **on_error()**. The **on_data()** method is called by tweepy when there is data in the stream to be read, and the data is passed as a string in JSON format; the **on-error()** method is called when an error occurs, and is passed a string with the error message. Creating this subclass will be described a little later. However, assume that it is called *tweet_listener*. The next step in the process is to create an instance of this class:

```
listener = tweet_listener()
```

The stream is accessed through this class instance. Now tell tweepy what this instance is so it can use it. Also do the authentication:

```
stream = tweepy.Stream(authentication, listener)
```

Finally, tell tweepy what to extract from the Twitter stream. For this example, the call is:

```
stream.filter(track=['Star Trek'])
```

but other parts of the stream can be accessed and sent to this program, such as times, dates, and locations. In this case, the track argument looks into the message text for the "Star Trek" string, case insensitive. Multiple search strings can be placed in the list: ['Star Trek', 'casablanca'].

What about the *tweet_listener* class? It is a subclass of *StreamListener*. The **on_data()** method needs to parse the JSON-formatted string it is passed and print the parts of the message that are desired. Since the **filter()** call restricts the messages to those containing the string "Star Trek," all that has to be done in this method is to print the body of the message. Here is the class showing the method; the explanation follows:

```
class tweet_listener(tweepy.StreamListener):

    def on_data(self, data):
# Twitter returns data in JSON format - decode it first
        dict = json.loads(data)
        print (dict['user']['location'])
        print (dict['user']['screen_name'],dict['text'])
        return True

    def on_error(self, status):
        print (status)
```

The parameter data is in JSON format. To convert it into something useable, pass it to the **json.loads()** method. It returns a Python dictionary with the data available, indexed by the field name. The data structure used by Twitter is complex, and is shown in small part in Table 13.1. The left side of the table shows the message field names, and the right lists some of the **user** fields; **user** is a field within the message that describes the sender. The variable **dict** is the resulting dictionary.

To simply solve the problem posed, all that would have to be done is to print **dict[‘text’]**, which is the message body. The value of **dict[‘user’]** is the data for the sender of the message. There is a lot of that, mostly not useful to anyone but an app developer (e.g., the background color of the user’s window), but **dict[‘user’]’[‘screen_name’]** is the Twitter identity of the sender, and **dict[‘user’] [‘location’]** often indicates where they are. It would be possible to collect data on where the largest number of tweets are being sent from, what kind of information is being conveyed, and in this way perhaps develop an early warning system for events happening in the world.

Table 13.1
Fields in a Twitter message

Message fields	Fields in the user structure
Coordinates (Coordinates) Represents the geographic location of this tweet as reported by the user or client application.	**created_at** (String) The UTC datetime that the user account was created on Twitter.
created_at (String) UTC time when this tweet was created.	**Description** (String) The user-defined string describing their account.

Message fields	Fields in the user structure
favorite_count (Integer) Indicates approximately how many times this tweet has been "liked" by Twitter users.	**geo_enabled** (Boolean) When true, indicates that the user has enabled the possibility of geotagging their Tweets.
Id (Int64) The integer representation of the unique identifier for this tweet.	**Id** (64 bit int) The integer representation of the unique identifier for this User.
in_reply_to_screen_name (String) If the represented tweet is a reply, this field will contain the screen name of the original author.	**Lang** (String) The code (BCP 47) for the user's declared user interface language.
Lang (String) When present, indicates a language identifier corresponding to the machine-detected language of the tweet text, or "und" if no language could be detected.	**listed_count** (Int) The number of public lists that this user is a member of.
Place (Places) When present, indicates that the tweet is associated with (but not necessarily originating from) a Place.	**Location** (String) The user-defined location for this account's profile. Not necessarily a location.
retweet_count (Int) Number of times this Tweet has been retweeted.	**name** (String) The name of the user, as they've defined it. Not necessarily a real name.
Source (String) Utility used to post the Tweet, as an HTML-formatted string.	**profile_image_url_https** (String) A URL pointing to the user's avatar image.
Text (String) The actual body of the message.	**screen_name** (String) The screen name or alias that this user identifies themselves with. screen_names are unique but subject to change.
User (Users) The user who posted this Tweet. (see: structure to the right) some attributes embedded within this object are unreliable.	**status** (Tweets) If possible, the user's most recent tweet or retweet. In some circumstances, this data cannot be provided and this field will be omitted, null, or empty.
withheld_in_countries (Array of String) When present, indicates a list of uppercase two-letter country codes this content is withheld from.	**statuses_count** (Int) The number of tweets (including retweets) issued by the user.
	time_zone (String) A string describing the Time Zone this user declares themselves within.

13.5 COMMUNICATING WITH OTHER LANGUAGES

Python is terrific for many things, but it can be quite slow. It is interpreted and has a lot of overhead for many of its features; dynamic typing does not come cheap. It may be difficult to easily access operating system functions from Python. C, C++, and other languages do not have these problems. It's possible to write a program in Python that calls, for example, a C program to do complex calculations of system calls.

Consider the problem of finding the greatest common divisor (GCD) between two integers; that is, the largest number that divides evenly into both of them. If the GCD between N and M is 1, then these numbers are relatively prime, and they could find use in a random number generator.

13.5.1 Example: Find Two Large Relatively Prime Numbers

This problem is solved using a C program to do the GCD calculation and a Python program to pass it large numbers until a relatively prime par is found. There are many C versions of the GCD program. This is a common first-year programming assignment. One such is gcd.c, provided on the accompanying disk:

```
#include "stdafx.h"
#include <stdio.h>

int _tmain(int argc, _TCHAR* argv[])
{
      long n,m;
    scanf("%ld %ld",&n,&m);
    while(n!=m)
    {
        if(n>m)
            n-=m;
        else
            m-=n;
    }
    printf("%d",n);
    return 0;
```

This is written for Visual C++ 2010 Express, but very similar code will compile for other compilers and systems. The basic idea is that it reads two large numbers, named **n** and **m**, determines their largest common divisor, and prints that number to standard output. The way that Python communicates with this C program is through the I/O system. C reads from the standard input and writes to the standard output. The Python program co-opts the input and output, pushing text data containing the values of n and m to the input, and capturing the standard output and copying it to a string.

This requires the use of a module named *subprocess* that permits the program to execute the gcd.exe program and connect to the standard I/O. A function named **Popen()** takes the name of the file to be executed as a parameter and runs it. It also allows the creation of *pipes*, which are data connections that can take the place of files. The **Popen()** call that runs the gcd program is

```
p = subprocess.Popen('gcd.exe',
                     stdin=subprocess.PIPE,
                     stdout=subprocess.PIPE)
```

Connecting **stdin** and **stdout** to *subprocess* PIPEs means that now Python can perform I/O with them. When GCD starts to execute, it expects two integers on input. These can now be sent from the Python program like this:

```
p.stdin.write(data)
```

The expression **p.stdin** represents the file connection to the program, and writing to it does the obvious thing. The Python program writes data to the C program, and the C program reads it from **stdin**. Data should be of type *bytes*, and should contain both large numbers in character form. Correspondingly, when the C program has found the greatest common divisor, it writes to standard output. This code is as follows:

```
s = str(p.stdout.readline())
```

The C program writes, and the Python program reads. The value returned is of type bytes again, so it is converted into a string.

The final Python solution calls the C program repeatedly until the GCD is 1:

```
import subprocess

n = 11111122
m = 121
data = bytes (str(n)+ ' '+str(m), 'utf-8')
while True:
```

```
p = subprocess.Popen('gcd.exe',
          stdin=subprocess.PIPE,
          stdout=subprocess.PIPE)
p.stdin.write(data)
p.stdin.close()
s = str(p.stdout.readline())
print (s)
if s == "b'1'":
    print ("Numbers are ", n, m)
    break
m = m + 1
data = bytes (str(n)+ ' '+str(m), 'utf-8')
```

This method of communicating with other languages is universal, but slower than passing parameters to functions and methods directly. There are a lot of problems with calling functions in other languages, not the least of which concerns typing. Python, which is a dynamically typed interpreted language, would make the programmer perform a significant amount of work to convert lists or dictionaries into a form that C or Java could use.

13.6 SUMMARY

Design by contract has designers create formal specifications for components, and using those involves a kind-of contract or agreement between programmers developing client software and those who built the modules and designed the protocols. For email, as an example, the sender and receiver have to agree on how to encode and decode a message, and how to access it from the network. To send mail between different computers always requires a standard, a scheme that is agreed upon by implementers of the system: a protocol.

The Simple Message Transfer Protocol is a specification of the process and data needed to send an email message. The Python module smtplib provides the methods needed to interface with this system, which is to say that smtplib implements SMTP and provides a programmer access at various places. There are two schemes for reading email: the Post Office Protocol (POP) and the more modern Internet Message Access Protocol (IMAP). An email client must agree to satisfy one of these. They Python module for IMAP is imaplib.

The File Transfer Protocol (FTP) is used to move entire files and directories across networks. It provides the same sort of interface to data on a distance computer as would be expected from a file system on a desktop. The ftplib module offers methods for handling this protocol. After authentication, commands are sent as character strings, and files can be sent or received using analogues of read and write operations.

FTP is built on top of lower level communication primitives such as sockets, which create bidirectional data connections between two programs on different computers.

Twitter sends out a stream of data containing all of the tweets sent by users, and the client can scan these for tweets that are of interest (subscribed). This stream can be captured using Python and the tweepy module, and automatic scanning of the feed can be done according to the user's program.

It is also possible for Python to communicate with other programs written in other languages by co-opting the input and output files for those programs and feeding data into and extracting results from the I/O channels.

Exercises

1. Write a simple email sending program *sendmail*. It should ask for the destination from the keyboard and accept the message that way, too. Multiple destination addresses can be specified by separating them with commas. The sender's email address and the server name should be built into the program.
2. Write an application that allows a user to specify a word or words and examines their mailbox for any email that contains them. The corresponding email messages should be written to a text file named "search.txt."
3. Write a Python program that downloads the files named "one.txt," "two.txt," and "three.txt" from an ftp site specified by your instructor into files of the same name on a desktop computer.
4. Design and code a server program that deals poker hands using the socket protocol. When the server is connected to by a client, the client sends a string "deal." The server should generate a random poker hand and send it as text. The spades suit in this scheme is as follows: s1, s2, s3, s4, s5, s6, s7, s8, s9, s10, sj, sq, and sk. Hearts are "h," diamonds are "d," and clubs are "c." Write a test program that reads and prints the resulting hands.

5. **DIFFICULT**. Write a two-player pong game using sockets. The game should display a graphical version of the standard Pong screen on the local and remote screens. The local player can move only the local paddle, and the motions made by the remote player are reflected on the local screen. The ball is positioned at the same place, as nearly as possible, on both screens simultaneously.

6. There are words and phrases that many governments use to indicate a potential security problem. They can examine emails and various social media outlets. Examine the Twitter stream for tweets containing the words "assassination," "security," "weapon," or "hostage." Print the tweet and location from which it claims to be sent.

7. How can the IP address of a distant site be determined? Search the Internet for that information as it can be implemented in a Python program, and implement a program that asks the user for a URL and returns an IP address for that URL.

Notes and Other Resources

Python *ftplib* documentation: *https://docs.python.org/3/library/ftplib.html*
Search criteria in IMAP: *http://tools.ietf.org/html/rfc3501#section-6.4.4*
Tweep download: *https://pypi.python.org/pypi/tweepy/3.4.0*
Tweepy intro: *http://docs.tweepy.org/en/latest/streaming_how_to.html*
How to use the Twitter API to stream tweets.
https://www.youtube.com/watch?v=pUUxmvvl2FE
Twitter message fields: *https://dev.twitter.com/overview/api/tweets*
Twitter user fields:
JSON Tutorial: *http://www.w3schools.com/json/*

1. Todd Campbell. (2002). *The First email Message*, *https://www.cs.umd.edu/class/spring2002/cmsc434-0101/MUIseum/applications/firstemail.html*

2. Tim Berners-Lee, Robert Cailliau, Ari Luotonen, Hendryk Nielsen, and Arthur Secret. (1994). *The World-Wide Web*, *Communications of the ACM*, *37*(8), 76–82.

3. Takeshi Sakaki, Makoto Okazaki, and Yutaka Matsuo. (2010). *Earthquake shakes Twitter users: Real-time event detection by social sensors*, in *Proceedings of the 19th International Conference on the World Wide Web (WWW '10)*, ACM, New York, NY, USA, 851–860.

Chapter 14

Parsing–The Structure of Data

In this chapter

Data has a structure to it. For data to be accessible to a computer, it must be in the form of numbers. There are no practical exceptions. The question of structure concerns the organization of these numbers: how are they ordered, how are they connected to each other in the sequence, what can the values be, and what information do they convey?

As one example, a sound file consists of a collection of numbers that each represent an audio sample, which is to say sound intensity, at some moment in time. Sound intensity was originally measured as the voltage in an electronic device, but in the file, it has a predefined range of possible values. The time difference between the samples can vary from file to file, but is fixed within any given file. There is usually a set of numbers at the beginning of the file that define the time between samples, legal range, and many other aspects of the file. In order to use a sound file, for example, to play it or edit it, one needs to understand the way the file is organized.

Parsing is the act of analyzing a sequence of symbols (which can be numbers) so as to extract information, perhaps with the goal of transforming or translating it.

Parsing is a fundamental task of many programs. At the very least, input to most programs is parsed to make sure it is legitimate, and it is then converted into a form that the program can use. It is one of the most common things that a program does, and yet little attention is paid to it when teaching computer science.

14.1 GRAMMARS

A *grammar* is a formal specification of the structure of some data item or collection. For the purposes here, we'll assume that data consists of characters, because in the context of parsing, that is frequently true. A grammar defines all possible forms that a dataset can take in a formal way. The structure of a CSV file has already been seen, so let's start with something simple yet common – a number.

An integer or floating point number is a sequence of characters that has a specific structure. FA grammar can be specified in multiple ways, but here we'll use a description called the *Backus–Naur form* (*BNF*). When using BNF, a symbol that is on the left side of the definition is defined by or can be replaced by a set of symbols on the right. This is called a *rule*. Here's an example:

```
<integer> ::= <digit> | <integer><digit>
```

The symbol on the left, "<integer>," is being defined. The symbol "::=" separates the symbol being defined from the definition. The definition here says that an "<integer>" can be a "<digit>" OR (the symbol "|") an "<integer>" followed by a "<digit">.

Any name enclosed in "<>" is called a *non-terminal* symbol, because it cannot appear in the final result. *Terminal* symbols are the actual components of what is being defined, which we call a *language*. Let's continue by defining a "<digit>:"

```
<digit> ::= "0" | "1" | "2" | "3" | "4" | "5" | "6" | "7" |
            "8" | "9"
```

This defines the abstract, non-terminal symbol "<digit>" as being any one of ten terminal symbols, which in this case are the characters "0" through "9." A digit is one of the numerals that form our number system. If we now define

```
<ssnumber> ::= <digit><digit><digit><digit><digit><digit>
               <digit><digit><digit>
```

we have a social security number, a nine-digit sequence. They are concatenated to form a long number.

Note that "<integer>" appears on the left side and the right side. This definition is *recursive*, but all that means is that it is defined partly in terms of itself. An "<integer>" can be one digit. The rule above for "<integer>" is really two rules separated by the OR symbol. It could be

```
<integer> ::= <digit>
<integer> ::= <integer><digit>
```

Let's label the rules. <integer> ::= <digit> is Rule 1a, and <integer> ::= <integer><digit> is Rule 1b, because they appear in the same rule. The rule for the digit could be Rule 2, and Rule 2a is <digit> ::= 0, and Rule 2b is <digit> ::= "1" and so on.

Now, consider the input "5." By this grammar, we can use Rule 2f to change the input symbol "5" into "<digit>." By Rule 1a, we can change this to "<integer>." This process of using rules to change the terminal symbols into target non-terminal symbol is *parsing*. Defined this way, it's pretty formal.

Now consider the input string "320." If we are trying to read an integer, we use Rule 2d to get the following:

```
<digit>20
Rule 1a to get          <integer>20
Then Rule 2c:           <integer><digit>0
Rule 1b:                <integer>0
Rule 2a:                <integer><digit>
Rule 1b:                <integer>
```

And we're done, because there is no more input.

Extended BNF offers things we can use. Items within square brackets are optional; they may be there or not. So

```
<postal code> ::= <letter><digit><letter>
                  [-]<digit><letter><digit>
```

could define a Canadian postal code. A code could be T2N1N4 or T2N-1N4.

Items in braces can appear zero or more times,

```
<integer> ::= <digit> {<digit>}
```

Or they can be suffixed with an asterisk ("*"), as in a regular expression:

```
<integer> ::= <digit><digit>*
```

Items that occur ONE or more times are suffixed with a "+:"

```
<integer> ::= <digit>+
```

Let's define a floating point number. It is a sequence of digits, or an "<integer>," possibly followed by a decimal point which is possibly followed by another sequence of digits. Here's one possible rule:

```
<float> ::= <digit>+ "." {<digit>}
```

Which demands one digit at least to the left of the decimal point. In this case "1.0" is legal but not ".12". Another option is

```
<float> ::= <digit>*  "."  <digit>+
```

which requires one digit at least to the right of the decimal point. In this case ".12" is legal, but not "0." What we need is one of the other. We need at least one digit and a decimal point. Simply combine these:

```
<float> ::= <digit>+ "." {<digit>} | <digit>*  "."  <digit>+
```

This discussion is very brief, and a full understanding of grammars and languages would take a great deal of time. What we need is an understanding of how to specify a language that we want to parse. The example language to parse is a simple programming language called PyJ.

14.2 PYJ AND JULIA

Julia is an interesting language designed to do fast numerical computations while allowing the syntactic and modular flexibility of *Python*. The *PyJ* language is used specifically in this chapter, and it is a much-abbreviated version of *Julia* with a correspondingly simpler syntax. It is a programming language and can be used for calculations. *PyJ* produces *C* code, which can be compiled and executed.

Here is an example *PyJ* program:

```
function sqr (a)
  return a*a
end

b = 2
```

```
while b < 20
  b = read()
  println( sqr(b) )
  b = b + 2
end
println()
```

Most programmers could puzzle out the syntax quickly and figure out what the program should do. That's not good enough to build a parser, though. A *PyJ* parser takes the input text and ends up at the "<program>" symbol. That's where the grammar begins:

```
<program> ::= { <function> } {<statement>}
```

which says that a program is a collection of function definitions followed by a collection of statements.

<statement> ::= <ifstatement> | <whilestatement> | <forstatement> | <assignmentstatement> |

<callstatement> | <printstatement> | <printlnstatement> | <returnstatement> |

<breakstatement> | <readstatement>

This lists all of the statement types in the language, of which there are ten. There are no declarations, because, like *Python* and *Julia* both, *PyJ* defines variables when they are used.

The statements are best illustrated by example first. An **if** statement is

```
if a<6
  k = k + 1
  println(k)
end
```

All **if** statements have a block of statements followed by an **end**. Options include **elseif** and **else** parts:

```
if a<6
  k = k + 1
  println(k)
elseif a>6
  k = k - 1
  println(k)
```

```
else
  k = 0
  a = 0
end
```

The indentation does not matter. A **while** statement is simple:

```
while a < b
    a = a + 1
end
```

A **while** followed by an expression followed by some statements followed by **end**. A **for** statement is as follows:

```
for i= 1:5
  print (i)
  println(i*i)
end
```

Here, the variable **i** takes on the values 1,2,3,4,5 in sequence. The **for** loop variable **i** is not available outside the loop. Assignment statements have already been used, but can assign any expression using standard operators and functions:

```
a = 3*5*(pi-3)/6
```

All variables are floating point and are defined when first used. If the user defines a function **sqr**, then it can be used in an expression, too:

```
dist = sqr(a-b)
```

The **print** and **println** statements print a value; println prints an end of line at the end, and print does not. The read statement prompts the user for input of a collection of variables:

```
read (x, peanut, zz)
```

All will be floating point numbers.

There is more to the syntax, but we have enough to begin. A systematic approach is important. When parsing any set of data, the process is first, to break up the input into symbols based on the original character data, and then to collect symbols into sets sequences that correspond to the language features.

14.3 LANGUAGE SYMBOLS AND SCANNING

Many symbols in a language consist of multiple characters. Some don't, like “>” and “<.” However “>=” is greater than or equal to and is two characters. An identifier, like a variable name, can be many characters, as can numeric constants. Some identifiers are special, like key words. “If” and “while” have special meanings and cannot be used as identifiers.

A *scanner* is a module that reads input characters and replaces them with symbols. In a parse, symbols are constants that take the place of more complex symbols, so the less than symbol “<” could be represented by a name **lessSy** that had the numeric al value 102. The name and value are arbitrary, but the idea is to simplify the input.

Consider the PyJ statement:

```
for control = (pi*pi):maxangle
```

As symbols, this could be represented as:

forsy ident eqsy lparen ident mult ident rparen colon ident

where each of those names was a number. The result could be

6 21 9 24 21 23 21 25 32 21

This is easier to handle in a parser, and the symbolic names can make the code easier to read. The complete list of symbols in PyJ is shown in Table 14.1.

Table 14.1
Symbols used in PyJ

numberSy	101	A float	greaterSy	111	>	functionSy	122	function
plusSy	102	+	lparenSy	112	(	ifSy	125	if
minusSy	103	-	rparenSy	113	)	whileSy	127	while
multSy	104	*	readSy	114	read	printlnSy	128	println
divideSy	105	/	commaSy	115	,	returnSy	129	return
equalSy	106	==	identSy	117	A name	printSy	130	print
lesseqSy	107	<=	elseSy	118	else	breakSy	131	break
noteqSy	108	<>	elsifSy	119	elseif	assignSy	133	=
lessSy	109	<	endSy	120	end	colonSy	134	:
greatereqSy	110	>=	forSy	121	for			

The scanner opens the input file and reads characters, either one at a time or into a buffer. In either case, characters are examined one at a time and are combined into symbols. At all times, there is a variable that contains the last symbol that was encountered: the *current* symbol. It is named **sy**. The parser makes its decisions based on the value of **sy**.

An essential function in the scanner is the one that gets the next character. It is named **nextCh**, and it looks something like this:

```
def nextCh ():
    global ch,eof

   if len(ch)==0:      # End of file means no more characters
        return eof
    try:
        ch = fp.read(1)  # Here we read characters one at a
time.
    return ch[0]         # Set global var ch and return it
```

If all characters are read into a buffer, then this code might look like this:

```
def nextCh ():
    global ch,eof, indx

    if length(buffer)<=indx: # End of file means no more
                             # characters
        return eof
    try:
        ch = buffer[indx]    # Here we read characters one
                             # at a time.
        Indx = indx + 1
    return ch               # Set global var ch and return it
```

Using a buffer is faster.

The next part of the scanner consists of some code that builds numbers and identifiers from characters. Building a number from characters has two parts, though. First is “is this a legal real number?” and the second is “what number is it?”. Both can be done concurrently.

```
def scanNumber():
    global numberVal

    numberVal = 0
```

```
    fracVal = 0
    while digit(ch):                              # Integer part
         numberVal = numberVal*10 + digitVal(ch)  # collect
                                                  # value
        nextCh()                                  # next digit?

    if ch == ".":             # Fractional part
        nextCh()
        fracVal = 0.0
        pten = 10.0

        while digit(ch):     # Each fractional digit has its
            fracVal = fracVal+digitVal(ch)/pten # Value
                                                # divided
                              # by 10 and summed.
            nextCh()          # Next digit
            pten = pten/10    # next power of 10
        numberVal = numberVal + fracVal
```

The **scanNumber** function is called when the scanner sees a digit. It accepts digits and accumulates a numerical value by multiplying the value of the digit by its appropriate power of ten. At the end of this, we have an integer value. If that is followed by a decimal point, then each digit that follows, if any, is part of a fraction. A fraction is accumulated by multiplying the digit values by a negative power of ten, or dividing by a power of ten, and accumulating a sum in the variable **fracVal**. When no more digits are seen, the resulting number is **numberVal + fracVal**.

The process for identifiers, which is to say variable and function names, is similar.

```
def scanIdent ():
    global ident
    ident = ""                # Start with empty string
    while identChar(ch):      # A letter?
        ident = ident + ch    # Add to the identifer
        nextCh()              # Get the next character
```

The global variable **ident** contains all of the characters in the identifier. Some identifiers are key words like "if." We'll work that out now. How do we know what an identifier means? We can look it up in a dictionary.

A global dictionary is created that stores symbols indexed by their identifier string. It's probably the simplest and fastest way to see if an identifier is a key word:

keywords["function"] = functionSy keywords["if"] = ifSy keywords["else"] = elseSy keywords["elseif"] = elseifSy keywords["for"] = forSy keywords["print"] = printSy keywords["println"] = printlnSy	keywords["read"] = readSy keywords["while"] = whileSy keywords["return"] = returnSy keywords["end"] = endSy keywords["break"] = breakSy keywords["read"] = readSy

If an identifier is found in this dictionary, then it represents the corresponding key word symbol. Otherwise, it is a variable or function name.

We are now ready to build the main scanner function, called **nextSy()**. This function is 60 lines long and is not reproduced here completely, but can be found on the website and on the accompanying DVD. However, the main parts of it can be described without seeing all of it.

It uses the global variable **ch** to determine what the next symbol will be.

If the character **ch** is a letter, then **nextSy** calls **scanIdent** to build an identifier string. It looks that up in the dictionary, and if found, then it returns the key word symbol, otherwise it returns the **identSy** symbol:

```
if letter(ch):
    scanIdent()
    try:
        k = keywords[ident]
        return k
    except:
        return identSy
```

In a similar way, if **ch** is a digit, then it scans and creates a number by calling **scanNumber** and returns the generic symbol for a number, **numberSy**:

```
if digit(ch):
    scanNumber()
    return numberSy
```

If **ch** is one of the single character symbols, then skip the character and return the symbol, like this:

```
if ch == "+":
    nextCh()
    return plusSy
elif ch == "-":
    nextCh()
    return minusSy
. . .
```

Finally, if the symbol consists of two characters (called a *digraph*) then we read another character and see if it fits as the second part. If so, read another and return the digraph symbol, otherwise return the original single character symbol, like this:

```
elif ch == "<":       # < can start one of thee symbols:
                      # < <= <>
    nextCh()          # Look at the next character
    if ch == "=":     # Is is '='. Then we have '<='
        nextCh()      # read another
        return lesseqSy  # Return <=
    elif ch == ">":   # OK, not '='. Is it '>'?
        nextCh()      # Yup. Skip the character
        return noteqSy  # And return <> (noteqSy)
    else:
        return lessSy   # Nope. It was just < (lessSy)
```

Notice that in all three case above, the value of **ch** is the next character in sequence, one that has not yet been used to build a symbol. This has to be true in all situations.

Now we have a scheme that will give us the next symbol in all cases. That's what the parser needs.

14.4 PARSING A PROGRAMMING LANGUAGE

A scanner translates characters into symbols. To a small degree, it parses symbols like numbers and identifiers, but those are low-level objects in this scheme. Parsing a language involves collecting symbols into meaningful structures, like statements. Many people don't really know how a compiler works. Once you understand how it works, you can never write a program again without that knowledge.

The parser here is simply one example of a parser of a general sort. HTML has a parser. So does SQL. Most complex input schemes do. Knowing how to parse properly means being able to handle more and more complex form of input and to perform increasingly involved computations. In the discussion that follows, one of the most complex parsing tasks is kept for last, and restricts the discussion somewhat. Parsing expressions is complex, and the grammar that we'll use is recursive. For the moment, let's assume that an expression is simply a number or an identifier.

14.5 WHILE STATEMENTS

Here is the syntax of a **while** statement in PyJ:

```
<while statement> ::= "while" <condition> <statement>+ "end"
```

The structure is that is starts with the while symbol **whileSy**, which is followed by a <condition>, followed by a number of statements until **end** is seen. A condition is a relational expression that results in true or false, such as **a < b**. So long as the result of that condition is true, the loop will continue to repeat. A basic parser would be

```
if sy == whileSy:                  # While statement
    sy = nextSy()
    condition()                    # The condition part
   while sy != endSy:             # Statements until the END
        statement()
    sy = nextSy()
```

Note that the fact that a while statement is coming is indicated by the fact that the current symbol is **whileSy**. It is skipped, then a condition is parsed by the function **condition()**. Then, as long as the current symbol is not **endSy**, a statement is parsed using the **statement()** function. Using this particular parsing scheme, which is simple but not the only parsing scheme, each non-terminal symbol is parsed by a function of the same name. Thus, according to the grammar, a while statement will call functions **condition** and **statement**, because they are non-terminal symbols. "While" and "end" are terminal symbols, and are skipped over.

One job of a compiler (not a parser) is to create a translation for the text being parsed. The translation is created while the text is parsed by generating code or some other text that allows the text that is being parsed to be executed or interpreted. In the case of PyJ, we will generate an equivalent *C* program. This makes it easy to test the compiler, as *C* can be converted by a *C* compiler into an executable file.

A PyJ while loop has correspondences to a *C* while loop:

```
while  x < 10                          while (x < 10)
                                  {
    statement                                statement;
    statement                                statement;
end                                    }
```

The above parse with code translation to C included in it is as follows:

```
if sy == whileSy:                   # While statement
    print ("while (")
    sy = nextSy()
    condition()                     # The condition part
    print (") {")
    while sy != endSy:              # Statements until the END
        statement()
    print ("}")
    sy = nextSy()
```

In general, for a legal input we get the following output:

```
while (   <condition>
) {
    <statements>
}
```

This should work if the condition and statements are legal.

14.6 FOR STATEMENTS

A **for** statement in *PyJ* has the syntax:

<for statement> ::= “for” <identifier> “=” <expression> “:” <expression>

<statement>+ “end”

Once again, we know that a **for** statement is coming because the current symbol is **forSy**, which is to say that we say the identifier “for.” Recall that each non-terminal is implemented by a function in the parser, so in this case we require the functions **identifier**, **expression**, and **statement**. The basic code is as follows:

```
if sy == forSy:                   # FOR statement
    sy = nextSy()
    if sy == identSy:             # Loop control variable
        sy = nextSy()             # skip it
        if sy == assignSy:        # Equals, skip
          sy = nextSy()
        expression()              # Start value
        if sy == colonSy:         #  skip the ':'
          sy = nextSy()
        expression()              # terminal value
       while sy != endSy:         # Statements until the END
           statement()
        sy = nextSy()
    else:
        println("Syntax error in FOR")
```

Error detection in this parser is lacking, because that takes a large amount of error unrelated to the basic task. If the **for** is not followed by an identifier, then an error will be indicated. There are many others that could have been tested for.

This code is only a parser, though. In the real language, there are code generation and other issues. This is a pretty simple **for** statement as languages go. There are semantic (meaning) issues that should be addressed, but that are not related to parsing. Here is the final code for the for loop with the code generation:

```
if sy == forSy:                      # FOR statement
    sy = nextSy()
    if sy == identSy:                # Loop control variable
        defineIdent(ident, FLOAT)    # define it -  symbol
                                     # table stuff
        lcvr = ident                 # remember it
        sy = nextSy()                # skip it
        if sy == assignSy:           # Equals, skip
          sy = nextSy()
        lcv = convertIdent(ident)    # symbol table stuff
        gen1n("for ("+lcv+"=")
        expression()                 # Start value
        gen1n("; "+lcv+"<=")         # Terminal condition
        if sy == colonSy:            # :  skip it
```

```
          sy = nextSy()
        expression()
        gen1("; "+lcv+"="+lcv+"+1) {") # Increment
        while sy != endSy:             # Statements until
                                       # the END
            statement()
        sy = nextSy()
        gen1("}")
        undefine(lcvr)                 # symbol table stuff
    else:
        println("Syntax error in FOR")
```

The PyJ **for** loop vs. the *C* **for** loop is as follows:

```
for var =  start : end         for (var=start; var end condi-
                               tion; var increment)
                               {
    statement                       statement;
    Statement                       statement;
end                            }
```

Here's how that translates:

```
   for var = start                  for (var = start;
         : end                      var <= end
                                    var = var + 1)
                              {
       statement                    statement ;
       statement                    statement ;
   end                        }
```

There are places in the commentary where it references the "symbol table." That is where we look up user defined symbols to see it they are defined and what they are. In PyJ, a symbol can be defined or not. If defined, it can be a floating point number or a function. A **for** loop control variable is defined in the **for** statement and is undefined at the end of the loop, so that it cannot be used outside of the loop.

14.7 IF STATEMENTS

If statements can have three components. First is

```
   if condition
       statement
```

```
    statement
end
```

The parser gets the **if** symbol, skips it, and expects a <condition> to follow. After that comes a sequence of statements, and if at any time an **end** is seen, then the statement is complete.

However, if the parser sees an **elseif** symbol before it sees the **end**, it begins to parse the **elseif** section of the **if** statement. **Elseif** is basically the same as the **if** statement:

```
elseif condition
    statement
    statement
end
```

There could be multiple **elseif** parts. Again, if the parser sees an **else** symbol before it sees the end, then it starts parsing the **else**:

```
else
    statement
    statement
end
```

This is just the **else** symbol followed by some more statements. The **end** must terminate the **if** statement after an **else**.

<table>
<tr>
<td><pre>def ifStmt():
    global sy, outf

    sy = nextSy()
    condition()

    while sy not in
            (endSy,elseifSy,
                    elseSy):
        statement()

    while sy == elseifSy:
      sy = nextSy()
      condition()
      while sy not in (endSy,
          elseSy, elseifSy):
        statement()</pre></td>
<td><pre>

    Skip the symbol if
    parse the condition

    any of end, elseif, or
    else could come after the
    set of statements
    Parse a statement

    So long as we see an
    elseif symbol
    Skip over it
    Parse a condition</pre></td>
</tr>
</table>

if sy == elseSy:	
sy = nextSy()	any of **end**, **elseif**, or
while sy != endSy:	**else** could come after the
statement()	set of statements
	If the symbol is now **else**
if sy == endSy:	skip it
sy = nextSy()	and parse a set of
else:	statements until an end
error(“**Missing END**	is encountered.
for IF”)	
	Skip over the end, if
	there
	Or indicate an error

14.8 EXPRESSIONS

Expressions are the hardest aspects of parsing many languages, at least for beginners. The complexity begins with the different precedence of operators: multiply and divide come before add and subtract, for example. Next, there is the issue of parentheses: grouping things in parentheses overcomes precedence rules, becoming effectively the highest precedence of all.

An expression is a hierarchy of structures based on order of evaluation. At the lowest level, with highest precedence, are the fundamental components which will be called *factors*. A variable (identifier) is a factor. So is a numerical constant. Also, so is any expression within parentheses. The grammar could be written as follows:

```
<factor> ::= <identifier>  |  <number> |  "(" expression ")"
```

The next lower in precedence are the multiplicative operations * and /. We'll call this component a *term*, and the syntax could be

```
<term> ::= <factor> { "*" | "/" <factor> }
```

According to this, the following are terms:

pi

12.6

pi*2/6*100

The first two are also *factors*, because a factor can be a term if not followed by an operator.

Now we have an *expression*, which consists of additive operators acting on terms.

```
<expression> ::=  ["+" | "-"]  <term> { "+" | "-"  <term>  }
```

According to this, the following are expressions:

12.5-(a – b – c)

-77.7

(a-b)*(a-b)

Basically, any numerical expression fits this grammar. Finally, we have *conditions*, which involve a relational (comparison) operator acting on expressions. The syntax is

```
<condition> ::= <expression> <relop> <expression>
<relop> ::= "<" | "<=" | "<>" | ">" | ">=" | "=="
```

A *condition* would be found in a **while** or **if** statement. So

if x < 10	"x < 10" is a condition
while x*x > 100	"x*x > 100" is a condition.

When generating C code for expressions, the program does the obvious things. The expression **a*b** in PyJ generates **a*b** in *C*, for example. The PyJ compiler always inserts parentheses to assert precedence, though. Some illustrative examples are shown in Table 14.2.

Table 14.2
Some PyJ and C expressions

PyJ	C	PyJ	C
a+b	(a+b)	a < b	(a < b)
a+(b*c)	(a+(a*c))	a+3 > 0	((a+3)>0)
12.2*c/d	(12.2*c/d)	a-3+c	(a-3+c)

14.9 FUNCTIONS

C has functions, so generating code is simple. On the other hand, functions in PyJ add complexity because there will be a function *definition* and also a function *call*. A function definition has the syntax:

```
<function> ::= "function" "(" { <identifier>
               { "," <identifier>} } ")" <statement>+ "end"
```

There is the key word **function**, a parameter list within parentheses, a set of statements, and an **end**. The parameter list is just a comma separated set of identifiers, but could be empty. There must be at least one statement in the body of the function.

Here is an annotation of the code that parses a function:

def functionStmt ():	
global sy, lexLevel	Skip the symbol FUNCTION
	Next should be an identifier
sy = nextSy()	Define it - it's the
if sy == identSy:	function name.
defineIdent (ident, FUNC)	Skip the function name
sy = nextSy()	symbol.
else:	
error("")	If no identifier, indicate
	an error.
if sy == lparenSy:	
sy = nextSy()	Next should be a "("
while sy == identSy:	Skip it
sy = nextSy()	If parameters exist, we will
if sy == commaSy:	not see **ident** , repeated
sy = nextSy()	Skip the ident
	Look for a comma,
if sy == rparenSy:	and skip if we find one
sy = nextSy()	If the next symbol is NOT an
	identifier, the list is done
while sy != endSy:	
statement()	The next symbol should be the
sy = nextSy()	closing parenthesis ")"
	Skip it
	Now the body of the function.
	Until an **end** is seen
	Parse a statement
	Skip the **end** symbol.

This code omits code generation and a couple of other things.

A function call can be a statement:

```
funcx( y )
```

or an expression

```
y = funcx(z)
```

A function returns a value, but it can be ignored. In the first case, the situation is handled by the **statement** function, which requires information that syntax does not provide – the kind of identifier seen. Here, is the syntax of an assignment statement and a call statement:

```
<assignment statement> ::= <identifier> "=" <expression>
<call statement> ::= <identifier> "("  { <expression list> ")"
```

Both of these begin with an identifier. How do we know what kind of statement we're looking at? The next symbol is "=" in one case and "(" in the other, so we could look ahead. This compiler has a table of names and their associated type. A variable has type FLOAT and a function has type FUNC, and so the parser does something different depending on the type of the identifier.

The compiler does not check whether the number of parameters defined is the same as the number passed.

14.10 EXAMPLES

The first example is simple, but will serve to introduce some aspects of the compiler that have been avoided until now. First is that there are some functions that are provided by PyJ, like reading and printing, that will be included by copying the *C* code into the output.

The other main new aspect here is that variable names have been changed. A variable named "xx" in PyJ will have a new, unique, name created for it in the resulting *C* program. The *C* variable var0_0 is the first variable declared as a global, which is level 0. The second variable is var1_0, and so on. Within a function, a new level of scope is defined, so the first variable there would be var0_1, for lexical or scope level 1. The following code section is a simple program showing all copied library code and new names.

a = 12 # a is var0_0
x = 21 # x is var1_0
y = a+(2-x) # y is var2_0
print(a)
	// Main.
	#include <stdio.h>
	int read ()
	{
	  int i;
	  scanf("Input: ", &i);
	  return i;
	}
	void print (int i) { printf ("%d ", i); }
	void println (int i) { printf ("%d \n ", i); }
	int main()
	{
	var0_0 = ((12));
	var1_0 = ((21));
	var2_0=((var0_0)) + (((((2))-((var1_0)))));
	ptmp = ((var0_0)))
	print(ptmp)
	}
	//Program complete.

From this point, the common code will not appear.

a = 1
x = 2
b = 3
print(a)
if x > a
  print(b)
end
	var0_0 = ((12));
	var1_0 = ((21));
	
	ptmp = ((var0_0)))
	print(ptmp)
	
	  if (((var1_0))None((var0_0)))
	{
	    ptmp = ((var1_0)))
	    print(ptmp)
	}

<table>
<tr><td><pre>a = 1
x = 2
b = 3
print(a)
if   x > a
  print(b)
elseif b > x
  print (x)
else
  c = a+b
  print(c)
end</pre></td><td><pre>var0_0 = ((1));
var1_0 = ((2));
var2_0 = ((3));
ptmp = ((var0_0)))
print(ptmp)
if (((var1_0))None((var0_0)))
{
  ptmp = ((var2_0)))
  print(ptmp)
} else
  if(((var2_0))None((var1_0)))
  {
    ptmp = ((var1_0)))
    print(ptmp)
  }
  else
  {
    var3_0 =((var0_0))+((var2_0));
    ptmp = ((var3_0)))
    print(ptmp)
  }
  }</pre></td></tr>
<tr><td><pre>function sqr (a)
  return a*a
end

b = 2
while b < 20
  b = read()
  println(sqr(b))
  b = b + 2
end
println()</pre></td><td><pre>float var1_0 (float var2_1)
{
  return ((var2_1)*(var2_1));
}

int main()
{
  var3_0 = ((2));
  while (((var3_0)) < ((20)))
  {
    ptmp = ((var3_0));
    print(ptmp);
    ptmp =((var1_0(((var3_0)))));
    println(ptmp);
    var3_0 = ((var3_0)) + ((2));
  }
   printf ("\n ");
}</pre></td></tr>
</table>

Finally, let's look at a practical example. Here is a program that implements a square root function using Newton's method, and prints roots for numbers between 10 and 20:

```
function sqrt (a)
  x = 1
  for i = 1:7
    x = 0.5*(x + a/x)
  end
  return x
end

i = 10
while i<=20
  println( sqrt(i) )
  i = i + 1
end
```

The output is as follows:

3.16228

3.31662

3.46410

3.60555

3.74166

3.87298

4.00000

4.12311

4.24264

4.35890

4.47214

Exercises

1. Conditions in PyJ do not have any **and**, **or** logical operators to combine simple conditions into more complex ones. For example, in PyJ we would have to code:
   `if i > 0`

```
    if i < 100
    …
    end
end
```

to accomplish what *Python* would using

```
if i > 0 and i  <100
```

Devise a syntax for adding **and**, **or**, **not** into a condition.

2. Create a parser for the following grammar:

```
<S> := 'a' S 'a' | 'e' S 'e' | 'i' S 'i' | 'o' S 'o'
       | 'u' S 'u' | 'x'
```

What kind of language does this represent?

3. A grammar can be said to *generate* a language. If non-terminal symbols in a grammar are mapped on to functions that each generate legal text for that component, the result is a program that can create legal examples of the language. For example, generating a factor in PyJ could be done as follows:

```
def factor ():

    if random() < 0.5:
         identifier()
    elif random()<0.7:
        number()
    else:
        print ("(")
        expression()
        print(")")
```

where the functions **identifier**(), **number**(), and **expression**() each generate legal examples of their kind. Create a generator for floating point numbers that uses the grammar in this chapter.

4. It should be possible to scan an input text line by line and determine, according to what is seen there, what the structure of the data is. Assume that there are the same number of data items on every line of a text file. Can you extract the data items without knowing in advance what the precise specification is? Under what circumstances might this fail?

5. Write a program that generates 50 instances of the language defined in question 2 above.

6. Create an extended BNF grammar for a line in a comma separated value (CSV) file.

Notes and Other Resources

Definition of CSV: *https://tools.ietf.org/html/rfc4180*
Download the Julia programming language: *https://julialang.org/downloads/*

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Grammar for Python-Julia (Pyj) – Small language for parsing practice

```
<program> ::= { <function> } {<statement>}
<statement> ::= <if statement> | <while statement>
               | <for statement> | <assignment statement>
               |<callstatement> | <printstatement> |
                <printlnstatement> | <returnstatement>
               |<breakstatement> | <readstatement>
    <function> ::= "function" "(" { <identifier>
                                   { "," <identifier>} } ")"
                                          <statement>+ "end"
    <if statement> ::=
    <while statement> ::= "while"  <condition>  <statement>+
                          "end"
```

```
<for statement> ::= "for" <identifier> "=" <expression>
                    ":"  <expression>
                            <statement>+ "end"
<assignment statement> ::= <identifier> "=" <expression>
<call statement> ::= <identifier>
                           "("  { <expression list> ")"
<print statement> ::= "print" "(" <expression> ")"
<println statement> ::= "println" "(" <expression> ")"
<return statement> ::=  "return" <expression>
<break statement> ::= "break"
<read statement> ::=  "read" "(" <variable list> ")"
<identifier> ::=  <letter>+
<variable list> ::= <identifier> { "," <identifier>
<float> ::= <digit>+ "." {<digit>} | <digit>*  "."
                                                  <digit>+
<digit> ::= "0" | "1" | "2" | "3" | "4" | "5"
                                | "6" | "7" | "8" | "9"
<factor> ::= <identifier>  |  <number> |
                                          "(" expression ")"
<term> ::= <factor> { "*" | "/" <factor> }
<expression> ::=  ["+" | "-"]  <term> { "+" |
                                            "-"  <term>  }
<expression list ::=  { <expression> {","
                                           <expression> } }
<condition> ::= <expression> <relop> <expression>
<relop> ::= "<" | "<=" | "<>" | ">" | ">=" | "=="
```

CHAPTER 15

COMMUNICATING USING GRAPHICS: WINDOWS, USER INTERFACES, AND PYGAME

In this chapter

Computers originally had very primitive means for providing input to programs. Early ones had to be rewired for each new program. Later, there were switches to enter binary instructions, paper tape, punched cards, and telex terminals and CRT monitors. That was merely the technology, though. The medium by which humans communicated with computers was using characters (text).

People have always used text and language for much of their communication. Given the technical limitations of computers, speaking to computers was not possible, so we typed programs and data in from a keyboard. This was the main source of input until the windows style of operating systems were created in the 1980s.

With the advent of *Microsoft Windows*© and the *Apple Macintosh*©, interfaces with computers moved towards more graphics and use of graphical interface devices like the mouse and, later, touch screens. Text still has a huge role, but modern software must take into account graphical interfaces and displays.

The knowledge of Pygame acquired so far is useful because of Pygame's ubiquity; it also allows programmers to construct computer games and graphics on multiple platforms.

Most personal computers come equipped with a drawing or painting program that allows a general user who is not a programmer to create a picture. Perhaps this could be for a presentation or a book or essay, or perhaps just for enjoyment. *Microsoft Paint*© is a good example of the genre. It provides a graphical interface for the selection of color, shapes, and other objects. Paint can import images in many formats and write the resulting edited image to a file. It can erase parts of a drawing and has the ability to back up some number of drawing steps so they can be redone. It can cut and paste parts of the drawing. Such a program would be a great example to illustrate the features of Pygame and the power of a graphical interface.

So, let's build a paint program that has these features. Only Pygame-offered facilities are used in the construction, and no other package will be needed. This program combines interaction and graphics.

15.1 A PAINT PROGRAM

There are many examples of a program designed for drawing or painting other than Paint. There is the new version, *Paint3D*. There is *Artweaver*, *Microsoft Fresh Paint, MyPaint,* or *Krita* for the PC, or *Paintbrush* for the Mac, and *Inkscape* or *GIMP* for Linux. The visual presence of each of these can be quite different, but all offer similar basic feature sets and each usually has some things at which they excel. Things these programs tend to have in common are as follows:

Drawing lines, circles, ellipses, and rectangles

Drawing text

Selecting a color, usually a foreground and a background color

Selecting a line thickness

Erasing

Saving

Loading and displaying an image.

Cutting and pasting

These features are selected using the mouse. Drawing options are chosen by clicking the mouse in a box, which places the program in the specific *mode*. Thus, clicking the mouse in the *draw line* box allows lines to be drawn with mouse clicks. Other options, such as color, are also selected by clicking in a box and setting a global parameter.

Interface

When designing the interface, simplicity is key. We need a drawing area within which all painting/drawing is done and an area of the screen where the options can be selected. Keeping the design simple, the drawing area will be on the top portion of the window that the program creates as the interface. It will have a fixed size of 800 x 600 pixels. Beneath the drawing area, which we'll call the *canvas*, in the same window, will be a set of boxes or buttons that will implement the options. Figure 15.1 shows a draft of this visual design.

The program is named *Mondrean* after the artist Piet Mondrean.

The x,y coordinate system of the window starts in the upper left at (0,0). At the lower right of the drawing area are the coordinates (799, 599). The parameter selection area starts at (0,600) and in this design covers the area to (650, 699).

Someone drawing using a mouse needs to know where, within the drawing area, the mouse cursor is. The X,Y coordinates of the mouse are drawn immediately below the canvas, and there is a set of calibration marks, one the right and bottom of the canvas, to help the artist determine exactly where they are. If the mouse is outside of the canvas, the X,Y position will not be given.

To draw something, the user depresses a mouse button and, possibly, moves the mouse elsewhere before releasing it. We can determine the location of the press and release easily through Pygame, and the action that will be taken depends on the current mode of the program. Is it drawing a line? A circle? And so on.

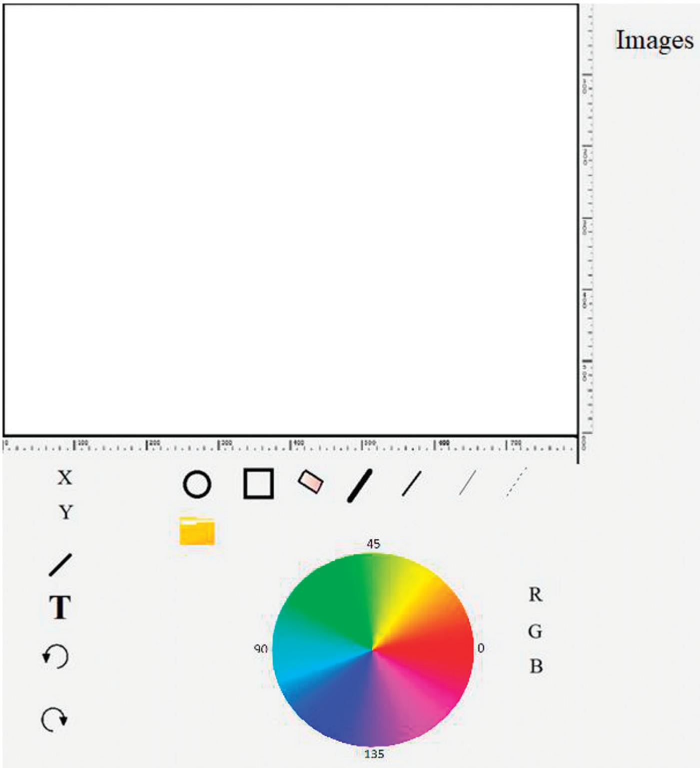


Figure 15.1
The *Mondrean* program interface.

This kind of analysis of how the program will be used allows us to decide what information we need from Pygame. We'll need to know is the location of the mouse and whether the mouse button has been pressed or released. For drawing text we'll need to accept text from the keyboard. That's really all that we need.

Drawing is done by noting the coordinates at which the mouse was pressed and released within the drawing area. A press starts the drawing, and a release ends it. For example, press the mouse button down for the start of a line, drag the mouse to the position that is desired to be the end of the line, and then release the button. An exception is text, where a click of the mouse indicates the beginning of the text.

Not only do we need access to the location of the mouse, but we need it frequently, often many times each second. Imagine that we're drawing a rectangle;

place the mouse cursor at the upper right corner of the rectangle we want, press the mouse button down and hold it, and move the mouse cursor to the lower right corner and let go of the button. This draws a rectangle. The program must check the mouse button many times each second to see if it has been pressed or released so that an accurate mouse location at the time can be gathered.

Now let's see how to do some basic drawing. To accomplish this, we once again use Pygame.

15.2 BUILDING THE MONDREAN INTERFACE

There are many aspects to the interface for this program, but there are two main ones: selecting and drawing. They are largely controlled by the mouse using positions and clicks, like most interfaces.

15.3 SELECTING

Selecting involves choosing a mode, action, or a parameter using the mouse. A *mode* is a way of doing something. We could be in circle, line, rectangle, or point mode, for example, in which the relevant object would be drawn using the mouse. One selects such a mode by clicking the mouse button while the mouse cursor is positioned within a box in the interface: clicking while the cursor in the circle box puts the program in draw circle mode.

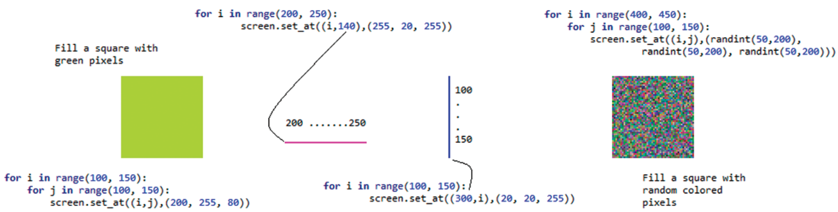


Figure 15-2
Various examples of setting pixels.

We can also select a *parameter*. Lines have three thicknesses that can be chosen, and a dashed line can be selected, too. We can choose a color with which to draw things.

We can also select *actions*. We can select that the program back up to the previous state or advance to a previously deleted one, we can save the current image, and we can load an image.

At this point in the design, there are 12 button type items on the screen 5 text boxes for output of position and color, and a color wheel for color selection. Unmentioned so far is a column of the right of the window for image file names. Images in the directory are listed here so that they can be placed into the canvas with a single click.

15.4 THE BUTTONS

We first discussed buttons and their implementation in Chapter 9. Recall that they work by detecting whether the mouse cursor lies within a specific rectangular region when a mouse button is clicked, and if so, then a specific action will be instigated.

Let's think of a button as a graphical interface object, which is best implemented as a *class*. Then we can create many instances of buttons anywhere we like while a degree of consistency in how they are handled. What we can do to a generic button is to

Draw it at a specific location.

Label it so the user knows what it will do.

Determine whether the mouse coordinates are within the button.

We therefore need to provide a button with a *position*, a pair of (x,y) coordinates at which it will be drawn, a *size*, which can be given as a width and height, a text *label* that can be empty, a *color,* and an *image* that can be drawn within the window (an icon). In Python, it might be valuable to specify a surface on which the button is drawn, which is usually (but not always) the monitor's screen.

Operations on a button will be implemented as methods. What is needed? We need to be able to set and get the label, color, and image. We need to know if the button is armed (the cursor is within the button area). We need to draw the button.

The following code is one implementation of a button.

<table>
<tr>
<td>

```
import pygame

# A basic screen button
# widget
class Button:
  def __init__(self,scr,
                xx,yy,w,h):
     self.x = xx  # Location:
                        (x,y)
      self.y = yy
      self.width = w
        # Size: width, height
      self.height = h
      self.label = ""
       # Text label
      self.scr = scr
       # Destination screen
# Button color
        self.color = (200,
                     200, 200)
        self.image = None
```

</td>
<td>

```
  def set_image(self, im):
    self.image = im

  def get_image(self):
    return self.image

  def set_label(self, s):
        self.label = s

  def get_label(self):
        return s

  def set_color(self, c):
        self.color = c

  def get_color(self):
        return self.color
```

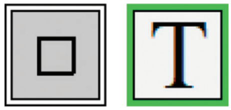
</td>
</tr>
</table>

The two most important functions need some annotation. First is **armed**, which determines whether the button can be turned on with a mouse click (is the cursor in the button):

```
def armed(self):
    m = pygame.mouse.get_pos()
# The pygame.mouse.get_pos() function returns a tuple (x,y)
# that tells us where the mouse is. Here, m[0] is the mouse X
# position and m[1] is the mouse Y position

    if self.x <= m[0] <= self.x+self.width and
                                # Is mouse X within the button?
       m[1]>=self.y and m[1]<=self.y+self.height :
                                # Is mouse Y within the button?
        return True             # Then the button is armed.
    return False                # No? Button not armed.
```

Finally, each button has a **draw** method that renders it to the screen. Here's what they look like:



The armed button is outlined in green. All buttons have a double outline and possibly an image indicating their function.

```
def draw(self):
    if self.armed():  # An ARMED button is drawn in green
        pygame.draw.rect(self.scr, (120, 220, 100),
            pygame.Rect(self.x, self.y, self.width,
                        self.height))

    else:             # Unarmed button is drawn in black.
        pygame.draw.rect(self.scr, (0, 0, 0),
        pygame.Rect(self.x, self.y, self.width,
        self.height), 1)

# The second, inner, rectangle in the outline.
    pygame.draw.rect(self.scr, (0, 0, 0),
    pygame.Rect(self.x+3, self.y+3,
            self.width-6, self.height-6), 1)
# Grey fill
    pygame.draw.rect(self.scr, self.color,
              pygame.Rect(self.x+4, self.y+4, self.width-8,
                          self.height-8))

# If there is an image specified then render it in the button.
    if self.image is not None:
        self.scr.blit(self.image, (self.x+4, self.y+4))
```

The entire Button class is only about 40 lines of code. Each one is given a destination Surface, a position, and a size then it is first created. Images and colors can be modified after instantiation. The setup for the circle but, as one example, is as follows:

```
# Create a surface for the button image
imageCircle = pygame.Surface((42, 42))
```

```
# Make the background of the button grey.
imageCircle.fill((200, 200, 200))

# Draw a circle
pygame.draw.circle(imageCircle, BLACK, (20, 20), 10, 2)

# Instantiate the button.
circleButton = Button(screen, 80, 750, 50, 50)

# Place the image into the button
circleButton.set_image(imageCircle)
```

Each button has to be drawn every time the screen is refreshed.

```
circleButton.draw()
```

And, finally, each button needs to be tested every time a mouse button is depressed to see if it has been invoked. We have written a function that checks all of the buttons:

```
def checkbuttons():
```

and to check the **circleButton**:

```
    .   .   .
if circleButton.armed():
    mode = CIRCLE
    .   .   .
```

When **circleButton** is pressed, it sets a global mode variable to CIRCLE, and that indicates what is to be drawn from now on.

Drawing

Whenever the mouse is positioned within the drawing area, drawing can be activated by pressing the mouse button. Whatever drawing state the program is in – line, circle, rectangle, text, or point – dictates what can be drawn. If the program is in LINE mode and the mouse is depressed, the mouse can be moved to a new position. Wherever the mouse button is released is the end point of the line. As the mouse is moved, a line is drawn temporarily on the screen to show what the like would look like. When the button is released, the line is drawn.

If the line is in circle mode, then when the mouse is depressed it defines the center of a circle. As the mouse is move, the radius of the circle changes and the circle is drawn temporarily on the screen and changes radius with the mouse position. When the mouse button is released, the circle becomes permanent.

The main loop of the Pygame program tests for events like the mouse button and key presses and releases. In this program, the mouse press usually establishes a starting point for an object, like a line or a circle. The user drags the mouse to another location and releases it, indicating a terminal position on the screen for the object being drawn. Doing the drawing is not difficult given the two mouse positions specified by the user. In the main loop, one must recall the point at which the mouse button was pressed and then when it is released the item can be drawn.

This is the obvious way to structure the program, but if it were done, it would be hard to remove items that have been drawn. Each line or rectangle is a different object on the screen. If the last item draw is to be erased, all of the other objects should be drawn except the last one. We have to remember all of the objects and their parameters. Moreover, if you think about it, they have to be redrawn whenever the screen is updated. Instead of drawing each item as the user defines them, we should save all of the user's drawing instructions someplace and then use them to draw the entire image each screen update. This is more complicated at the outset in the design phase, but later simplifies implementation.

Let's look at the main drawing operations and construct a data structure that can store them.

For a rectangle, the mouse button is depressed at the upper left (or perhaps lower right) corner of the polygon. When the mouse is released, the cursor position defines the opposite corner. Other factors that influence the drawing are the current color and the line thickness. All of these items must be saved. A possible structure is as follows:

```
[102, [x0,y0], [x1,y1], [r,g,b], t]]
```

This is a *list*, and the first element, in this case 102, is a code that indicates what is being drawn. 102 is the code for a rectangle. This is followed by the start point, the end point the color, and the line thickness. This list, which we'll call a *drawing directive* or *DD*, has the following structure:

[Integer List List List Integer] = [code, start point, size, color, line thickness]

The drawing directive for a line is much the same, but the third component is not a size but an endpoint for the line. The user presses the mouse button to define the start point and releases it to define the end point. These two points define the line.

[100 [x0,y0] [x1,y1] [r,g,b] [t]]

The DD for a circle has the same structure. The point where the mouse button is pressed defines the center of the circle. When the button is released, that point is used to calculate the radius, because that's how Pygame specifies a circle. The radius is the distance between the points where the button was pressed and where it was released. That point is stored as the second coordinate and will be used to calculate the radius, which is a floating point number. So for a circle, we have

[101, [x0,y0], [x1,y1] ,[r,g,b], t]

For text, a mouse click (a press and a release) defines the starting point for the text. The user then types text from the keyboard, which is saved as a string to be drawn at that point. This string can be stored in the DD:

[103, [x0,y0], "String", [r,g,b], t]

Erasing is like defining a rectangle. Mouse button down to begin defining a rectangular area to be erased, button up to finish the definition. Everything in that region will be set to the background color.

[104, [x0,y0], [x1,y1], [r,g,b], t]

This defines what can draw at this stage of the design. When the user draws something, the program creates the drawing direction for that and places it at the end of a list, which is named **backstack**. The entire drawing can be created by starting at element 0 of **backstack** and drawing each of the items through to the end of the list. This is actually done by the program. Each time though the main Pygame look the screen is cleared and all of the items are redrawn.

The **backstack** is a list of instances of a class named **Mode**, which implements the drawing directive. Assuming that **backstack** contains all of the items drawn, in proper order, then redrawing them can be done as follows:

```
def draw():
    for i in range(0, backstack.N):    # For each DD
        op = backstack.get(i)          # Get the item
```

```
    if op is None:
        return

    k = op.getkind()          # The operation (code)
    a = op.getstart()         # Start coordinats (x,y)
    b = op.getend()           # End coordinates x,y)
    c = op.getcolor()         # Color value (r,g,b)
    t = op.getthickness()     # tline thickness (real)
    s = op.getstring()        # Text string
                              # (for TEXT command)

    if k == LINE:    # If the code is dfor drawing a
                     # line, do it
       pygame.draw.line(screen, c, (a[0], a[1]), (b[0],
                            b[1]), t)
    elif k == CIRCLE: # if the code is for a circle,
                      # draw it.
        r = round(distance(a, b)) # a is center,
                                  # b is release point
        if r > t:                 # Radius is distance
                                  # between the two
            pygame.draw.circle(screen, c, (a[0], a[1]),
                                 r, t)
    elif k == RECTANGLE:  # If the code is for a
                          # rectangle, draw it
        pygame.draw.rect(screen, c, (a[0], a[1], b[0]-
                            a[0], b[1]-a[1]), t)
    elif k == TEXT:  # If code is for TEXT
                 . . .
    elif k == ERASE: # If code is for erasing, draw a
                     # filled box
        pygame.draw.rect(screen, (255, 255, 255),
                (a[0], a[1], b[0]-a[0], b[1]-a[1]), 0)
```

We've left the drawing of text until last. Drawing text requires a font and a known size. In Pygame, text uses a font that has been initialized by the programmer. We could use the text() function invented in Chapter 7. A different font variable would be used for each font in cases where many sizes are needed. We could, for example, use the following:

```
times20 = pygame.font.SysFont('Times Roman', 20)
times30 = pygame.font.SysFont('Times Roman', 30)
              .     .     .
```

15.5 IMAGES AND SURFACES

A Pygame *Surface* type represents an image. Images saved as files can be read in to a Pygame surface using the function pygame.image.load.

```
S = pygame.image.load("image.png")
```

There are other important functions to know about for images. There are others:

```
S.get _ size()
```
– gets the image size, as a tuple (x,y)

```
S.copy()
```
– Returns a copy of S

```
S.fill(color)
```
– Fills the entire image with pixels of the specified color.

```
S.subsurface(r)
```
– Return a part of a bigger surface. The pixels are shared, so changes in one will be seen immediately in the other. The variable **r** is a tuple (x, y, width, height) that defines a rectangular region in **S** to return.

There is a module named **transform** that contains methods for modifying surfaces. The most important methods are

```
pygame.transform.scale( Surface, (width, height) )
pygame.transform.rotate(Surface, angle)
```

Let's take a break from the paint program and do a quick example with images. There is a file named "impression.jpg" that holds an impressionist image of a sunflower. It can be read into a *Surface* in a few lines of code and displayed within a short event loop. The image, named **img1**, can be resized to be 100 x 100 pixels and drawn in a different location. Resizing is done as suggested above, using

```
img2 = pygame.transform.scale( img1, (100, 100) )
```

Finally, for this example, we'll take a sub-image of img1and display it under the rescaled version:

```
img3 = img1.subsurface((200,200,200,200))
```

Each of these images can be displayed on the main Surface by *blitting* them to it as described above. The resulting canvas is shown in Figure 15.3.

```
import pygame

screen = pygame.display.set_mode((1100, 900))
```

```
clock = pygame.time.Clock()
pygame.font.init()

img1 = pygame.image.load("impression.jpg")
img2 = pygame.transform.scale( img1, (100, 100) )
img3 = img1.subsurface((200,200,200,200))
while True:
  clock.tick(10)
  screen.fill((255,255,255))
  screen.blit(img1, (0,0))
  screen.blit(img2, (730, 100))
  screen.blit(img3, (730, 300))
  pygame.display.update()
# redraw the screen
```

Figure 15.3
Output from the example image program.

15.6 STACKS: UNDRAW AND REDRAW

The mechanism for undrawing things should be pretty clear now, but to summarize: when something is drawn by the user, it is saved in a list, and not drawn immediately. Every 1/30 of a second, the event loop calls the draw function, which scans all the drawn items and redraws them.

When the undraw button is pressed using the mouse, it moves the last item from the **backstack** list to the end of a second list called **forestack.** Since that element is now not in the **backstack** list, it will not be drawn. Each time the undraw button is used, another item is moved from the end of **backstack** to the end of **forestack**, effectively undrawing it. If the redraw button is pressed, the item at the end of **forestack** is moved back to the end of **backstack**, meaning that it will reappear in the drawing.

Whenever the user draws something new, whatever it may be, the **forestack** list is emptied.

The names **backstack** and **forestack** refer to the fact that these lists are being used as *stack* data structures. A stack is organized so that the last thing saved will be the first thing seen, as would be the case in a pile of books, for example. If a math book is placed on a table, then a history book and then a novel, we have a stack of books. On the top of the stack is the last thing I put there – the novel. If I remove that from the stack, I uncover the next-to-last book I placed there, the history book. Items are removed from the stack – *popped*, it is called - in reverse order from the way they were put there. This is also called a *first-in-last-out* (*FILO*) structure.

Figure 15.4 details how this works using a simple example.

The **backstack** is not only used as a stack. It is, as has been described, also used as a simple list when redrawing the screen. When used as a stack, it is accessed from the end; when used to redraw, the items are accessed from the start (element 0) through to the last one.

A stack should be implemented as a class. The stack uses a list, so when adding a new element to the end (called *pushing*), we **append** a new item to the end of the list (top of the stack) and when an item is *popped*, it is removed from the end. However, when drawing, we can scan the list from element 0 through to the top and redraw everything in the order it was drawn originally.

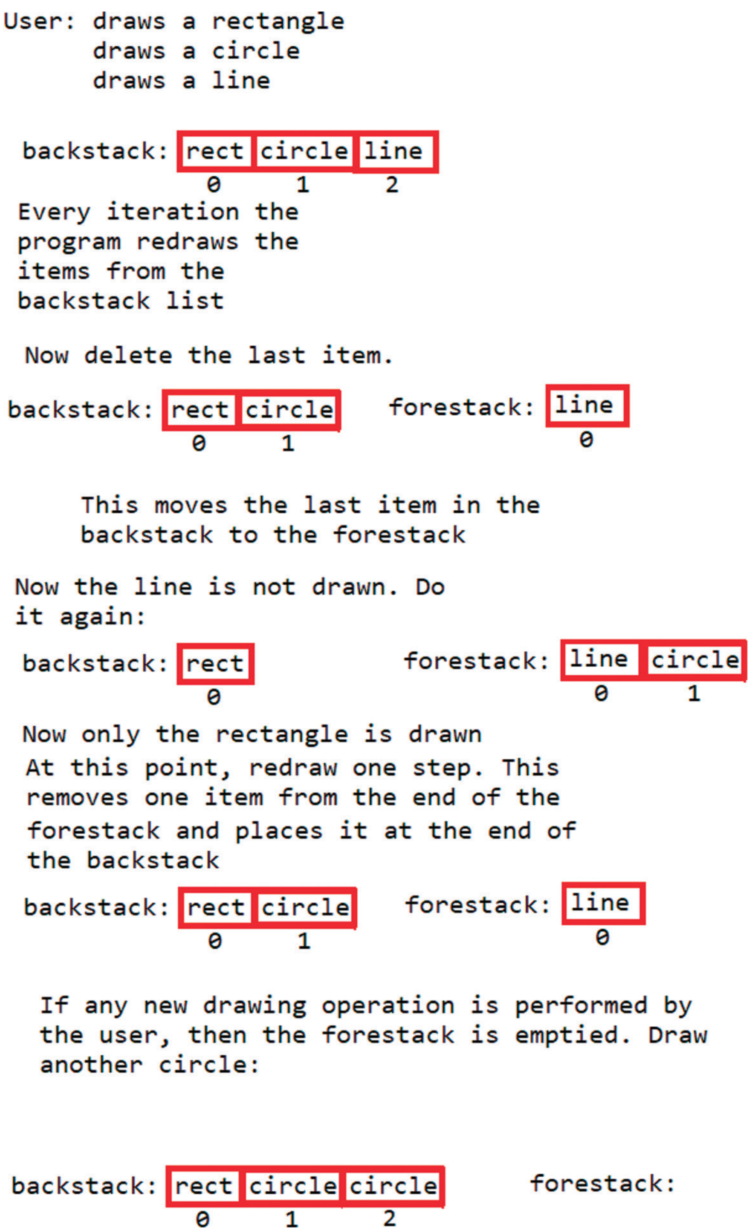


Figure 15.4
Use of a stack to save drawing operations.

An example stack that does what we want is given in the following code:

```
# Stack class for the
# Paint program
class Stack:

    def __init__(self):
        self.elements = []
        self.N = 0

    def pop(self):
        if self.N == 0:
            return None
        x = self.elements[-1]
        self.elements = self.
elements[0:self.N-1]
        self.N = self.N - 1
        return x
```

```
def push(self, x):
    self.elements.append(x)
    self.N = self.N + 1

def top(self):
    if self.N <= 0:
        return None
    return self.
        elements[self.N-1]

 def get(self, i):
     if i >= self.N:
         return
     return self.elements[i]

def getsize(self):
    return self.N
```

Because python is so flexible about types, this stack can be used for floats or integers, or anything really. In the case of the paint program, it will be used to push and pop drawing instructions, which will be instances of the class named **Mode**, which is an implementation of a drawing directive.

```
# Data structure for
# PAINT modes

class Mode:
    def __init__(self, kind,
                 a, b, c, d):
        self.md = kind
        self.start = a
        self.end = b
        self.LINE = 100
        self.CIRCLE = 101
        self.RECTANGLE = 102
        self.TEXT = 103
        self.erase = 104
        self.color = c
        self.thickness = d
```

```
    def getend(self):
        return self.end

    def setkind(self, k):
        self.md = k

    def getkind(self):
        return self.md

    def setcolor(self, c):
        self.color = c

    def getcolor(self):
        return self.color

   def setthickness(self, t):
        self.thickness = t
```

```
    def setstart(self, a):
        self.start = a

    def setend(self, a):
        self.end = a

    def getstart(self):
        return self.start
```

```
    def getthickness(self):
       return self.thickness

    def setstring (self, s):
        self.end = s

    def getstring(self):
        return self.end
```

15.7 COLOR SELECTION

Choosing a color could be done using buttons, as it done in the Paint program, but that limits the number of colors significantly. How many buttons can be provided? Instead, *Mondrean* provides a color wheel that shows a large number of distinct colors. When the user clicks on a pixel in this wheel, that color is used as the current color. Simple for the user.

Figure 15.5 shows the color wheel, which is drawn at (500,680) in the display. That's the upper left coordinate of the image, which is 200 × 200 pixels in size. This means that the center of the circle is at 500+100, 680+100, or 600, 780. The radius is 100. Thus, if the distance from the mouse position to (600,780) is less than 100 when the mouse button is clicked, then the user is selecting a color. What color? The one right beneath the mouse cursor, of course. This is acquired using the call

```
currentColor = screen.get_at((mouseX, mouseY))
```

where the variables **mouseX** and **mouseY** hold the current mouse position as returned by the call

```
pygame.mouse.get_pos()
```

in the event loop. The variable **currentColor** always contains the color being used to draw with.

After this was implemented, it was discovered that there was no way to select any shade of grey, including the very popular colors white and black. A second selector was added to the color disk, in this case, a rectangular one that has a color range from black through grey values to white. When the mouse button is released in this region, it sets the color to the grey level that is under the mouse cursor.

15.8 IMAGE FILE SELECTION

On the right side of the **Mondrean** screen is a list of file names that the program has decided are images based on the file suffix. It only recognizes **jpg** and **png** right now. If the user clicks on one of these names, then the corresponding image should be displayed in the drawing area; if the image is too large, it will be cropped.

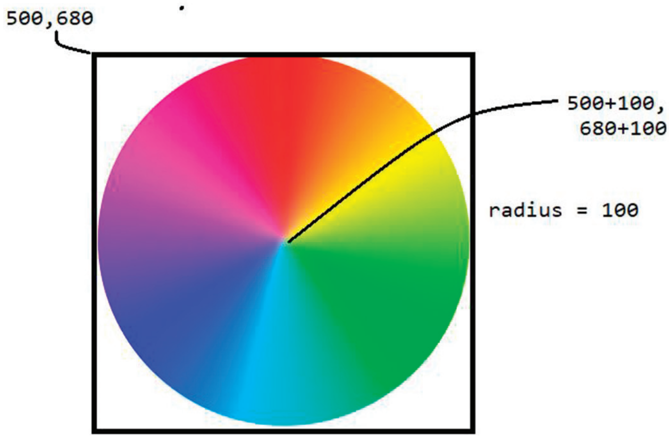


Figure 15.5
The color wheel used to select drawing colors.

This has four parts to the implementation: the image files have to be recognized in the working directory and their names copied to a list; we have to determine when a mouse button is clicked while the cursor is over one of the names; that image file must be read in to a Surface; and the resulting Surface must be blitted to the drawing area.

A problem is that, because of the way things are drawn, the image will not appear on the screen unless placed there by the **backstack** scanning function. In other words, we have to add a new drawing directive for images. This is instructive, because adding any new drawing feature would have to do the same.

Looking in the current working directory for image files is a new kind of task. It involves the use of an of operating system related function named **listdir**, which examines the directory passed as a parameter and returns all of the file names as a list. For example, on a PC,

```
names = listdir("C:\Program Files")
```

results in a list of file names from the "Program Files" directory being assigned to the variable **names**. Printing this out could result in

['7-Zip', 'Android', 'Application Verifier', …..

In particular, **listdir(".")** gives a list of the files in the *current* directory. Image files end in ".jpg" or ".png," so we need the following code:

```
allFiles = listdir(".")      # Create a list of image files
fileList = []
for i in allFiles:
    if i[-3:]=="jpg" or i[-3:]=="png":
        fileList.append(i)
```

This creates a list in **fileList** that contains only image files.

Determining which name the mouse is pointing to is simple, and we've done it many times before:

```
def filenameScan():
    k = (trunc(mouseY)//30)
    y = k * 30
    pygame.draw.rect(screen, (255, 0, 0),
                                    (800, y, 100, y), 1)
    return k
```

This is based on a text height of 30 pixels, a location of (800,0) for the upper left corner of the file name list, and w width of 100 pixels. This function returns with the 30-pixel-high rectangles the mouse is in, which is the index for the file name list of the file selected.

When the mouse button is pressed while the cursor indicates a name, we load that file into a *Surface*.

```
k = filenameScan()
imag = pygame.image.load(fileList[k])
```

Now, we have to create a new drawing descriptor. Let's define mode 105 as IMAGE mode, and create a new DD as follows:

```
thisdraw = Mode(IMAGE, [0,0], [imag], currentColor,
                                          thickness)
```

Parameter [0,0] is where the image will be drawn; [imag] is the actual surface that was just created with the image in it. None of the rest matters in this case. Finally, in order that this be visible on the canvas, we must place it in the **backstack**:

```
backstack.push(thisdraw)
```

After adding code to draw that will draw an image DD, we're done:

```
if k == IMAGE:
    imag = b[0]
    xx,yy = imag.get_size()
    if xx > 800:
        xx = 800
    if yy > 600:
        yy = 600
    screen.blit(imag.subsurface(0,0,xx,yy), (2, 2))
```

Now we can select and draw an image, and even undo it if we like.

The source code for *Mondrean* is available online and on the DVD. It is under 400 lines long, and reading through it could complete your understanding of the methods used to create a graphical interface.

Exercises

1. Some paint programs use different cursors depending on what operation is being performed. Pygame has a facility for switching cursors. Do some research on how to do this, and use a different cursor when the CONTROL key is depressed than otherwise.

2. Create a cursor that looks like crosshairs, and show that it works in a simple program.
3. An interactive graphics program can be made to draw arbitrary polygons. Devise such a program that uses the mouse to identify consecutive points and then draws the polygon when a point is selected very close to the initial point.
4. Create a program that loads an image file and uses the mouse to select a part of it, crop it, and save it. (Resizing the display window is possible, but not required: try it.)
5. Sometimes it can be useful to *magnify* a part of an image. Create a program that loads and displays an image, and that magnifies the portion of the image that is under the mouse cursor by a factor of 2.

6. Lines are drawn as sets of pixels that are next to each other so that they seem to create a line. There is an algorithm that does this: it takes a start and end point, and sets pixels in between to create a line. This algorithm is generally called a DDA (digital differential analyzer). Locate such an algorithm in the literature and implement it using Pygame. Compare lines drawn with it and those drawn by **pygame.draw.line**.

7. The *clone tool* in Photoshop copies pixels from one portion of the image to another. This is used to remove unwanted elements from a photograph. To use it, hold down the ALT key while depressing a mouse button on a location in the image (location A), then, keeping ALT depressed, move the mouse and release the button again elsewhere (location B). The relative location of these two positions (a vector AB) is used now as the way to define the source of pixels to be copied – when the mouse is clicked from now on, pixels in that location will be replaced by a copy of those in the same distance and Then release the ALT key. When the mouse is clicked from now on, the region under the mouse cursor will be replaced with pixels from a part of the image found in the AB direction. (There could be a bug in Pygame.)

Notes and Other Resources

PyGame Tutorial – Game Development Using PyGame In Python *https://www.edureka.co/blog/pygame-tutorialSearch* criteria in IMAP: *http://tools.ietf.org/html/rfc3501#section-6.4.4*

Graphics using Python 3: *http://anh.cs.luc.edu/python/hands-on/3.1/handsonHtml/graphics.html*

Graphic Design in Python using Pygame and turtle: *https://freshlybuilt.com/graphic-design-in-python-using-pygame-and-turtle/*

References

1. *https://www.tutorialspoint.com/computer_graphics/line_generation_algorithm.htm*
2. James D. Foley, Andries van Dam, Steven K. Feiner, John F. Hughes (1990). *Computer Graphics: Principles and Practice.* Addison-Wesley Professional.
3. James R. Parker (2019) *Game Development Using Python*. Mercury Learning.
4. Al Sweigart (2012). *Making Games with Python & Pygame. http://inventwithpython.com/makinggames.pdf*

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