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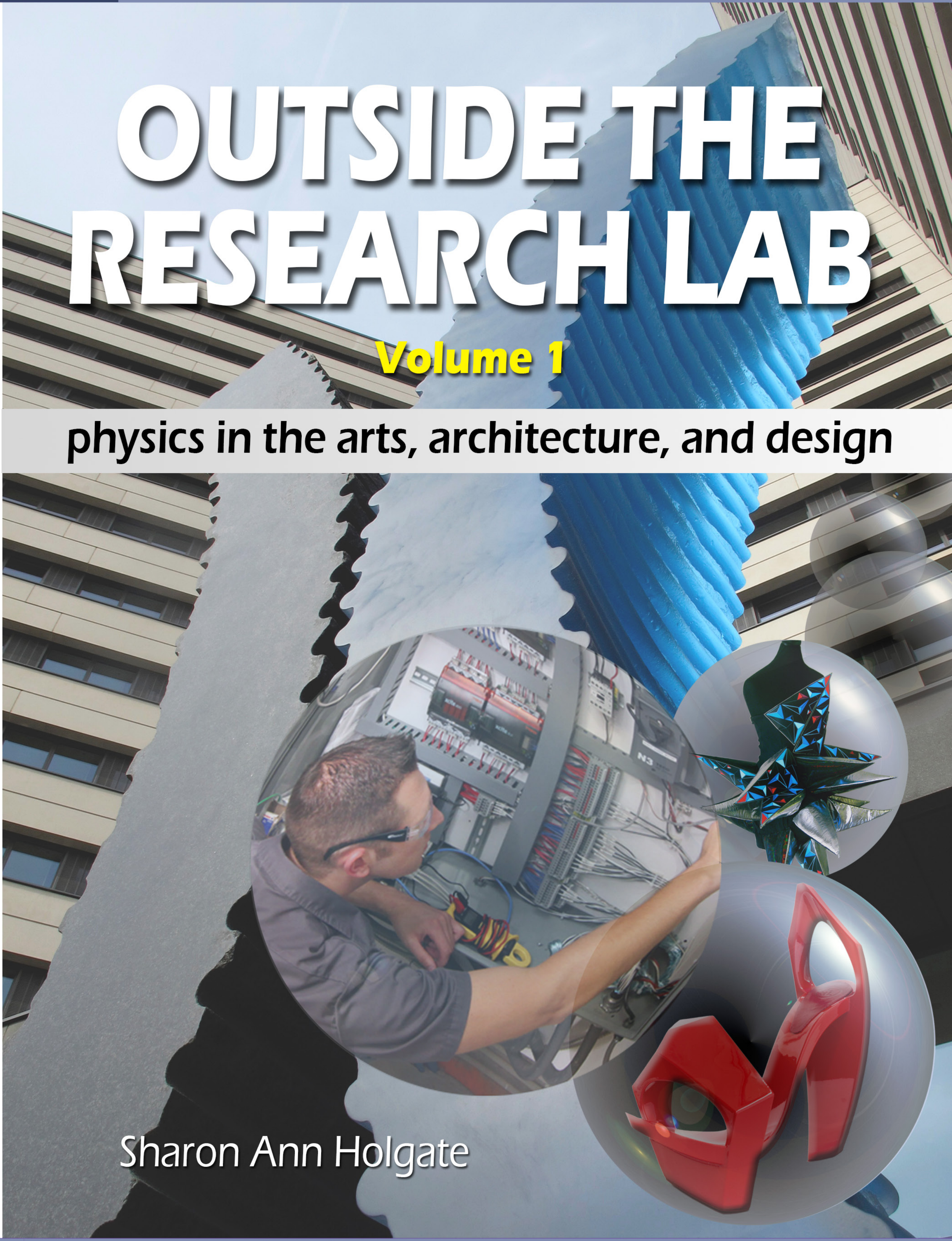

OUTSIDE THE RESEARCH LAB

Volume 1

physics in the arts, architecture, and design

Sharon Ann Holgate

IOP | ebooks

Outside the Research Lab

Volume 1: Physics in the arts, architecture and design

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Sharon Ann Holgate
Science writer and broadcaster, doctor of physics

Morgan & Claypool Publishers

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For Annabelle, Chantelle and Louis, in the hope they never lose their curiosity about the world around them.

Contents

Preface

Perhaps surprisingly for someone fascinated by physics from an early age, I never planned to study the subject at university. Instead I grew up with my heart set on a career in the entertainment industry, and spent my teenage years training as a singer and trying to learn all I could about stagecraft and how to survive in show-business. During school holidays I could often be found in the wings of various theatres around the UK watching friends performing in shows, and studying their interactions with the audience.

Of course I was only allowed to stand in certain places so that I was not only out of sight of the audience but also well out of the way of scenery, props, and lighting being moved around by the stage technicians. My curiosity about science coupled with a growing habit for asking questions about anything I didn't understand meant I was soon familiar with some of the physics and technology used in theatrical productions.

After a nasty bout of glandular fever damaged my singing voice, I needed to rethink my career options and as a result I applied to take a degree in physics. Fast forward through my doctorate and nearly 20 years of working as a freelance science writer and broadcaster and those early experiences, together with my fondness for visiting art galleries and learning about fashion history and different disciplines of design, led me to come up with the idea for this book which explores some of the physics and technology inherent to the arts, design and architecture.

My main aim for the book is to give students, and other interested readers, an insight into the diverse range of applications for physics outside of the scientific research environment. To help achieve this, I have chosen to cover several different areas of the arts and design ranging from stage lighting to the creation of sculpture. In each case I have interviewed experts working in that sector, who have generously given up their time to explain how physics and technology impact on their work, and also provided some stunning images.

Since I am hoping this book will be useful for readers with a wide range of backgrounds, I have kept the number of equations low, and explained the less familiar scientific terminology and notation. I have also presented the more detailed physics in boxes interspersed among, but separate from, the main text.

I make no apology for choosing to write about topics that I have a personal interest in—and in some cases have previously written articles or broadcast about—as I suspect I won't be alone in my enthusiasm for these subjects! I hope they will not only provide an interesting general read, but also some useful examples of how the physics encountered in taught courses relates to the real world. As someone who has written extensively about careers, and has had to re-assess their intended professional path, I also hope the contents of this book might inspire readers as yet undecided on their future career, or looking for a change in direction, to think about career options that they might not otherwise have considered.

Acknowledgements

It goes without saying that I could not have written this book without the help of many people. I would first like to thank my editor Nicki Dennis for approaching me to write for the IOP Concise Physics series, and for her help developing my initial idea for this book into the finished product. Thanks are also due to Karen Donnison and Mitra Sayadi at Morgan & Claypool, and Jacky Mucklow at Institute of Physics Publishing.

In addition, I'd like to extend my gratitude to all the interviewees who have kindly given their time, expertise and advice, and allowed me to reproduce some fantastic images. I could not have written this book without your enthusiasm and support. I would also like to thank the various press officers and personal assistants who helped me to secure interviews and kindly provided me with additional information. These include Dennett Arlott from The Sculpture Studio, Bethany Bull from the Royal College of Art, Georgina Carter at Marks and Spencer, Dawson Chance, Paul Crognale at Shure, Judy Green, Vicky Kington and Erin Lee at the National Theatre, Bernhard Lott from Siemens, and Cam Whitelaw at IWS. Thanks are also due to Amanda Kernot, Margaret Mason, Peter Palmer, Mike Ttoouli, and Tracey deWhalley for their help in various ways with this project.

As ever friends and family members have been a tremendous support, in particular Colleen Bridgnell, Larry Crockett, David Culpeck, Andrew Fisher, Julian Mayers, Derek Palmer, Ian Rennison, Rob Scovell, Emma Winder, my Uncle Les Edmondson, my cousin once removed Tony Sparkes, and my mother Joan.

Finally I would like to thank Chris and Don, my favourite baristas, for keeping me fuelled with hot chocolate and bourbon biscuits, and providing a friendly ear on occasions when neighbouring building work forced me to work out of my office.

About the author

Sharon Ann Holgate

© Sharon Ann Holgate. Photo by Stuart Robinson.

Sharon Ann Holgate has a doctorate in experimental physics from the University of Sussex in the UK, where she was a Visiting Fellow in Physics and Astronomy for nine years, and is a Chartered Scientist and Chartered Physicist. She has worked for nineteen years as a freelance science writer and broadcaster, with broadcast credits including presenting on the BBC World Service and BBC Radio 4, presenting video podcasts for medical research charity the Myrovlytis Trust and appearing on a 'Boffins Special' of The Weakest Link. Her articles have appeared in *Science*, *Science Careers*, *New Scientist*, *The Times Higher Education Supplement*, *E&T*, *Flipside*, *Focus*, *Physics World*, *Interactions*, *Materials World*, *Modern Astronomer*, and *Astronomy Now*, while her first book *The Way Science Works* (a children's popular science book co-authored with Robin Kerrod) was shortlisted for the Aventis Prizes for Science Books Junior Prize. She was a contributor to the popular science book 30-*Second Quantum Theory*, and her undergraduate textbook *Understanding Solid State Physics* is currently in use as a core text in universities around the world. She has also written careers material, case studies, and press releases for the Institute of Physics and careers material and brochures for The Institute of Physics and Engineering in Medicine, and given talks at venues including the Science Museum in London. Dr Holgate was the Institute of Physics Young Professional Physicist of the Year for 2006, won a Merit Award in the 1994 Daily Telegraph Young Science Writer of the Year competition, and was shortlisted for the radio programme category of the Association of British Science Writers' Awards in 2005. Outside of work she collects contemporary ceramics, is a regular visitor to art galleries and museums, and enjoys learning about fashion history and steam locomotives. Her CV, and further information, may be seen at www.sharonannholgate.com

Chapter 1

Introduction

Whether you're hearing about the latest physics breakthroughs on the news, or attending university lectures and labs given by physicists, it can be easy to think of physics as purely an academic subject that is separate from the other aspects of your life. But physics does more than just describe how all types of matter and energy behave, and so reveals how almost everything around us, and even within us, works. Physics-based technologies are integral to many of the everyday work and leisure activities we carry out when science is the last thing on our minds.

In this book we will explore applications of physics in the visual and performing arts, as well as in the design of some of our houses, and of our clothing and footwear. We will see how professionals in many different fields use physics and physics-based technologies in their day-to-day working lives. We will also discover how in some cases developments in physics have led to revolutions in seemingly unrelated areas.

For instance, as we will see in chapter 2, physics is utilised by sculptors who are creating public artworks with the help of laser-line generators, CAD packages (see figure 1.1), flame cutting, and the results of stress calculations.

Chapter 3 describes how theatrical productions are enhanced thanks to modern variations on physics-based techniques that have helped wow audiences for centuries. While stage lighting has changed dramatically since the torches and candles used to light some of the earliest productions, the rope and pulley systems used to raise and lower scenery have changed very little in the last 400 years.

Many of us also enjoy being entertained in the comfort of our own homes via television and radio. Chapter 4 explores the physics behind sound recording for radio and television, while chapter 5 reveals how musical instruments create their own distinctive sound and how professional musicians harness physics phenomena to help them produce the sounds they want.

In chapter 6 we hear how ultrasound and laser welding are starting to be used by the fashion industry for mass manufacturing of seam free garments, and how some designers are incorporating physics-based technologies into their clothing

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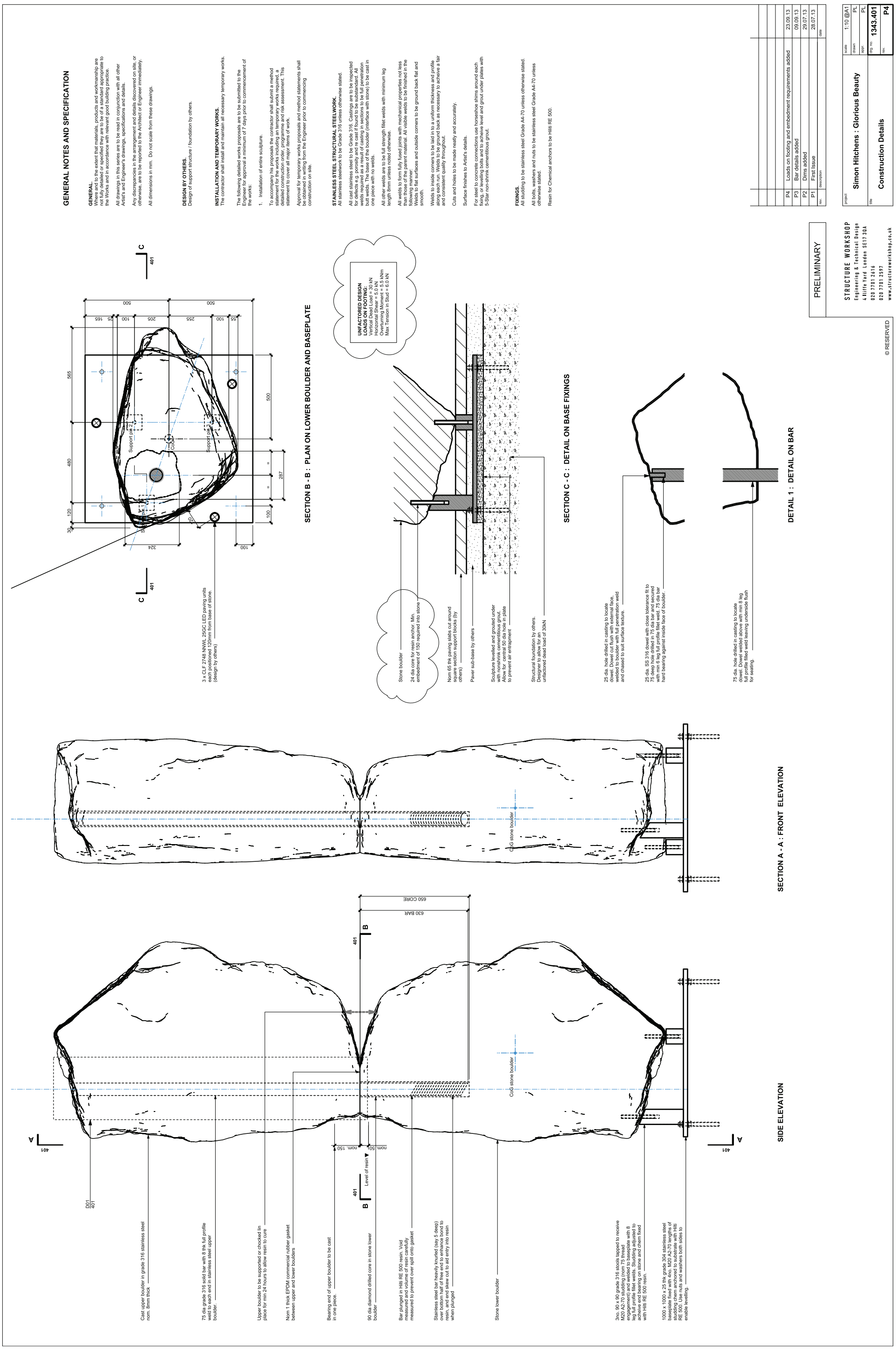

GENERAL NOTES AND SPECIFICATION

GENERAL.
Where and to the extent that materials, products and workmanship are not fully detailed or specified they are to be of a standard appropriate to the Works and in accordance with relevant good building practice.

All drawings in this series are to be read in conjunction with all other Artist's and Engineer's drawings, specifications and details.

Any discrepancies in the arrangement and details discovered on site, or otherwise, are to be reported to the Architect or Engineer immediately.

All dimensions in mm. Do not scale from these drawings.

DESIGN BY OTHERS.
Design of support structure / foundation by others.

INSTALLATION AND TEMPORARY WORKS.
The contractor shall install and maintain all necessary temporary works.

The following detailed works proposals are to be submitted to the Engineer for approval a minimum of 7 days prior to commencement of the works:

1. Installation of entire sculpture.

To accompany his proposals the contractor shall submit a method statement for the works including an temporary works required, a detailed construction order, programme and risk assessment. This statement to cover all major items of work.

Approval for temporary works proposals and method statements shall be obtained in writing from the Engineer prior to commencing construction on site.

STAINLESS STEEL STRUCTURAL STEELWORK.
All stainless steelwork to be Grade 316 unless otherwise stated.

All cast stainless steel to be Grade 316. Castings are to be inspected for defects e.g. porosity and re cast if found to be substandard. All welds required as a result of casting in sections to be full penetration butt welds. The base of the boulder (interface with stone) to be cast in one piece with no welds.

All other welds are to be full strength fillet welds with minimum leg length 8mm unless noted otherwise.

All welds to form fully fused joints with mechanical properties not less than those of the parent material. All visible welds to be finished in the following manner:
Welds to flat surfaces and outside corners to be ground back flat and smooth.

Welds to inside corners to be laid in to a uniform thickness and profile along each run. Welds to be ground back as necessary to acheive a fair and consistent quality throughout.

Cuts and holes to be made neatly and accurately.

Surface finishes to Artist's details.

For steel to concrete connections use horseshoe shims around each fixing, or levelling bolts and to acheive level and grout under plates with 5-Star non-shrink cementitious grout.

FIXINGS.
All studding to be stainless steel Grade A4-70 unless otherwise stated.

All bolts, washers and nuts to be stainless steel Grade A4-70 unless otherwise stated.

Resin for Chemical anchors to be Hiliti RE 500.

rev.	description	date
P4	Loads on footing and embedment requirements added	23.09.13
P3	Bar details added	09.09.13
P2	Dims added	29.07.13
P1	First Issue	28.07.13

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project	Simon Hitchens : Glorious Beauty	scale	1:10 @A1
		drawn	PL
		appr.	PL
title	Construction Details	drg. no.	1343.401
		rev.	P4

Figure 1.1. CAD drawings of the stainless steel and stone sculpture *Glorious Beauty* by Simon Hitchens, including details of the 75 mm diameter stainless steel rod stabilising the structure, and the underground stainless steel base plate with welded-on stainless steel blocks which the sculpture is bolted and resin bonded to. (© Simon Hitchens. Reproduced with permission.)

Figure 1.2. *Thunderstorm dress* by Amy Winters, with electroluminescent panels which respond to sound detected via an embedded microphone and sound sensor. (Photograph © Amy Winters. Reproduced with permission.)

(see figure 1.2). This chapter also describes how physics can be used to produce innovative footwear designs (see figure 1.3).

The final chapter, chapter 7, discusses the role of physics in producing sustainable and visionary architecture. As this chapter reveals, physics-based technologies such as solar panels and heat exchangers are enabling buildings to use much less energy (see figure 1.4), while the possibilities offered by augmented reality are inspiring visionary architects.

For each chapter, I have spoken with experts working in the respective fields, who have given an insight into their work and how physics impacts on it. Additional details about the physics mentioned, and related physics topics, are presented in boxes interspersed among the main text.

Throughout this book I have used the S.I. system of units when describing the sizes of measurable physical quantities—which include mass, length, pressure, electric charge, and time. This system of units—Système Internationale d'Unités

Figure 1.3. Resin shoe by Chau Har Lee made by 3D printing. (Photo by Charlotte Visser. Courtesy of Chau Har Lee. Reproduced with permission.)

Figure 1.4. Siemens new HQ in Munich, Germany has a range of features to make it as sustainable as possible. These include triple glazing, solar panels that will generate about a third of the building's electricity, and LED luminaries that consume around half the electricity required by conventional lighting. (Courtesy of Siemens. www.siemens.com/press.)

to give it its full title—is, as its name suggests, the internationally agreed system for detailing the sizes of physical quantities. One of its main advantages is removing any confusion that can be created by using different systems of units to describe the size of the same quantity, and hence having to convert numbers from one unit to another. Such as, for instance, converting a temperature measured in Fahrenheit into its S.I. unit of Celsius. Table 1.1 shows a selection of physical quantities along with their associated S.I. unit, while table 1.2 lists the prefixes used to describe multiples of S.I. units.

As table 1.2 reveals, some prefixes are uppercase, and others are lowercase. It is important not to muddle the two as the same letter can represent very different sized units. For example, lowercase m stands for milli while M denotes mega. Different countries can vary in how they use S.I. units. In some countries for instance drinks are labelled in cl while in other countries the labels show the quantity in ml.

Table 1.1. Some physical quantities and their respective S.I. units.

Physical quantity	Name of S.I. unit	Symbol of S.I. unit
mass	kilogram	kg
time	second	s
length	metre	m
electric current	ampere	A
electric potential	volt	V
luminous intensity	candela	cd
illuminance	lux	lx
force	newton	N
pressure	pascal	Pa
power	watt	W
frequency	hertz	Hz
energy	joule	J

Table 1.2. Prefixes used to describe multiples of S.I. units (a) getting smaller, where 10^{-3} is a shorthand way of writing 0.001, and 10^{-6} is equivalent to 0.000001, and so on. Part (b) shows the prefixes for getting bigger, where 10^2 is equivalent to 10 × 10 i.e. 100, and 10^3 is mathematical shorthand for 10 × 10 × 10 i.e. 1000, and so on.

(a)			(b)		
Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^2	hecto	h
10^{-3}	milli	m	10^3	kilo	k
10^{-6}	micro	µ	10^6	mega	M
10^{-9}	nano	n	10^9	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
10^{-18}	atto	a	10^{18}	exa	E
10^{-21}	zepto	z	10^{21}	zetta	Z
10^{-24}	yocto	y	10^{24}	yotta	Y

Table 1.3. The Greek alphabet.

Capital letter	Lowercase letter	Name
Α	α	alpha
Β	β	beta
Γ	γ	gamma
Δ	δ	delta
Ε	ε	epsilon
Ζ	ζ	zeta
Η	η	eta
Θ	θ	theta
Ι	ι	iota
Κ	κ	kappa
Λ	λ	lambda
Μ	μ	mu
Ν	ν	nu
Ξ	ξ	xi
Ο	ο	omicron
Π	π	pi
Ρ	ρ	rho
Σ	σ	sigma
Τ	τ	tau
Υ	υ	upsilon
Φ	φ	phi
Χ	χ	chi
Ψ	Ψ	psi
Ω	Ω	omega

As Greek letters are used to describe some of the quantities covered in this book, table 1.3 provides a quick reference point for the Greek alphabet.

Each chapter concludes with some suggestions for further reading and a selection of web links—including links to video footage and additional photographs—that will enable the work of the various interviewees, and in some cases the physics topics covered, to be explored further.

Although there are some trends emerging, it is difficult to foresee exactly what impact current physics research will have on the arts and design. But for the next few decades at least the influence of physics, and the technology it helps create, looks set to continue shaping not only the aesthetics of our surroundings, but how we are entertained, and what we wear.

IOP Concise Physics

Outside the Research Lab

Volume 1: Physics in the arts, architecture and design

Sharon Ann Holgate

Chapter 2

Where art meets technology—using physics and materials science to create and install sculptures

2.1 Introduction

When we stop to look at a public sculpture, we are likely to consider a range of things such as its shape and form, what the sculpture means to us, how we feel about its relationship with its environment, and whether we actually like it or not. But how many of us think about what goes into creating and installing that artwork? As this chapter will reveal, physics and materials science play a large part in bringing public sculptures to life.

We will first hear how sculptor Simon Hitchens, whose intriguing work I originally encountered at an exhibition in 2010, has used physics and technology to help create public sculptures in a variety of materials including stone and polyurethane resin. This includes employing a CAD package, and carrying out stress calculations. Sculptor Juanjo Novella then explains how his beautifully intricate machine-cut steel sculptures—which I discovered online while researching for a *Materials World* feature—are brought to life with the help of computers and industrial flame cutting machines.

Thanks to my favourite sculptor Philip Jackson, whose studio work of masked Venetian figures has captivated me for over 20 years, we will next discover the steps taken to create work ready for casting in bronze. Philip also reveals how he uses laser-based technology to help with the welding together of his sculptures after casting.

Sarah Craske and Stephen Melton who operate a foundry at SPACER then describe the basic steps in the centuries-old ‘lost wax’ casting process. I first interviewed Sarah and Stephen for my *Materials World* feature (which forms the origin for this chapter) having discovered Sarah’s work via a book she has written about bronze casting (see references). In this chapter we will see how they are evolving the lost-wax process via their commitment to the use of greener materials and green energy.

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The chapter concludes with a look at the working practices of Jonathan Hateley, a sculptor whose work I first admired at a sculpture exhibition in 2009. Jonathan describes how he creates works in bronze resin thanks to the use of a range of materials including fibreglass and silicone, and a diamond grinding tool.

2.2 Working with varied materials

For Simon Hitchens, a UK based sculptor whose public commissions include *Unity* in King's Cross, London, (see figure 2.1) and *Glorious Beauty* in Kensington in London (see figure 2.2), physics and computing are often an integral part of the creative process. He sometimes uses computer modelling prior to beginning a sculpture if he needs to create a CGI model as well as a physical one to show the

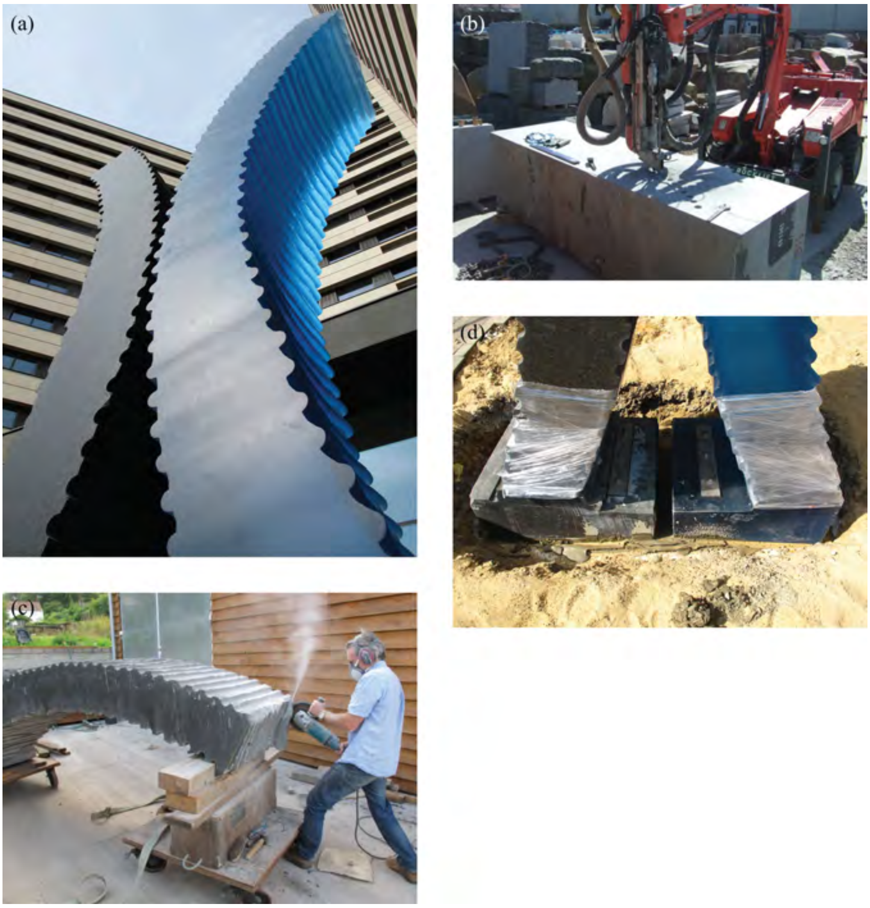

Figure 2.1. *Unity* by Simon Hitchens. (a) The sculpture *in situ* in King's Cross, London; (b) *Unity's* granite block being cut; (c) Simon using a power tool to carve the granite half of *Unity*; (d) holding down bolts going through the resin and granite bases of *Unity*. (© Simon Hitchens. Reproduced with permission.)

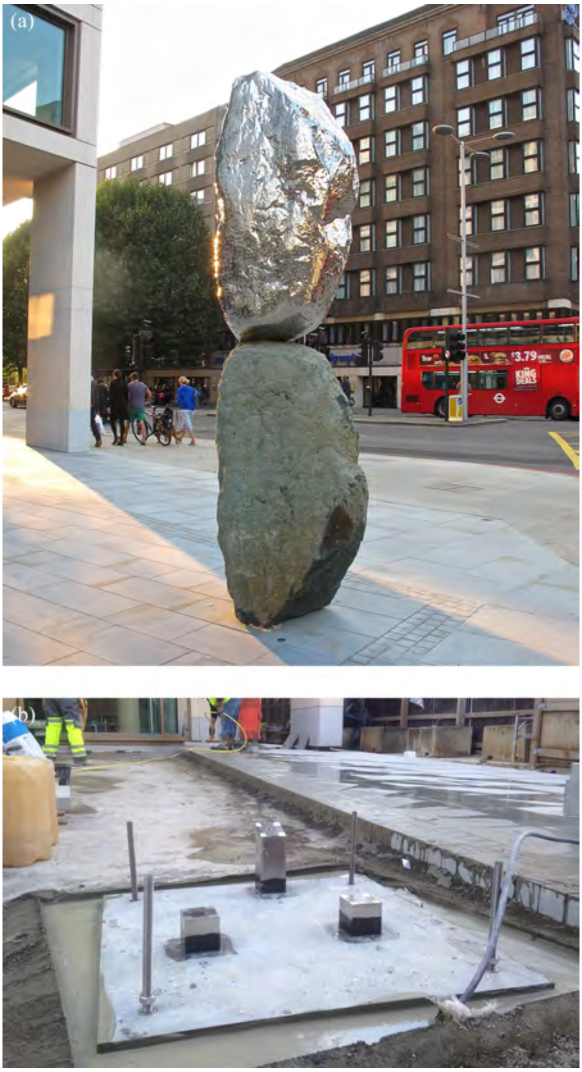

Figure 2.2. *Glorious Beauty* by Simon Hitchens. (a) The sculpture *in situ* in Kensington in London; (b) the base showing the three stainless steel blocks welded to a stainless steel base plate that the sculpture is bolted and resin bonded to. (© Simon Hitchens. Reproduced with permission.)

prospective sculpture to clients, and has used technology in various ways to create his finished works.

‘I find it really fascinating to make sculptures that I have to scratch my head about how on earth it is going to be made. It’s worth getting up in the morning if I’ve got a challenge to do something new and different and push my limits [by] working technologically or materially in different ways,’ says Simon.

He first used a digital method of creation for *Glorious Beauty*, which has a lost wax cast (see section 2.5) stainless steel top section that closely mirrors a garnet amphibolite boulder beneath (see figure 2.2(a)). ‘I took the boulder, laser scanned it, and [digitally] flipped the boulder turning it inside out to make the mirrored form of the stainless steel section,' he explains.

For another sculpture, this time made from stone, Simon used CAD to turn his drawings and calculations of the sculpture into a 3D digital model. This could be twisted around and sliced up to help him determine down to the millimetre where to place the guide lines for cutting into the raw stone block from the quarry.

Computers are also employed to carry out calculations to ensure his public sculptures are safely supported. The external forces acting on sculptures can come from accidental collisions, high winds, vandalism, people climbing over them, or from their own weight, explains Simon, who sometimes consults structural engineers to calculate these stresses. The results of their stress calculations together with their computed values for the centre of gravity, toppling points, and thermal expansion rates enable Simon to design suitable bespoke supports and bases for his sculptures. (See box 2.1 for more on stress.)

'Most of my sculptures are reasonably heavy and they actually stand up quite happily under their own weight without any securing or pinning. Obviously that can't happen in the public realm, but they are that stable. So if you then mechanically fix them to large concrete foundations you cannot push them over. These sculptures are designed to be up for 100 years and look as good, hopefully, as they do today,' continues Simon, whose sculptures are generally supported by stainless steel.

For example, *Glorious Beauty* is stabilised via 'a 600 mm long stainless steel solid rod about 75 mm in diameter. This goes from the very top inside the hollow stainless steel boulder, through its bottom where it touches the stone boulder and then carries on for 600 mm down into the heart of the stone where it is resin bonded in place.

Box 2.1. Stress

In physics and materials science, stress is defined as the force per unit cross-sectional area acting on a material object. When stress is applied to a solid material, it causes the material to deform and so change shape. The S.I. derived unit for stress is the pascal (Pa), which is named after the French mathematician and physicist Blaise Pascal (1623–62). 1 Pa is equivalent to 1 N m^{-2} (one newton per square metre), as can be seen from the following simple equation for stress

$$\sigma = \frac{F}{A} \tag{2.1}$$

where σ is the stress in pascals, F is the force in newtons and A is the cross-sectional area in metres squared of the solid material that the force is acting on.

There are three different types of stress: tensile stress, compressive stress, and shear stress. Each type causes a different change in shape, as shown in figure 2.3. While tensile stress pulls on an object and stretches it, compressive stress squeezes an object and squashes it, and shear stress creates a distortion.

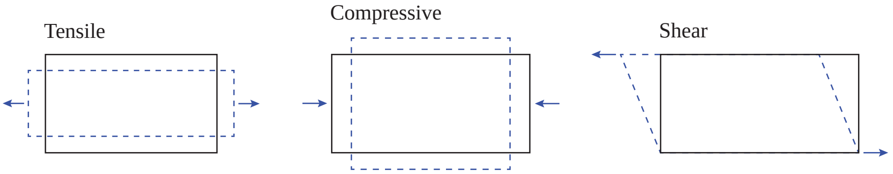

Figure 2.3. The type of deformation produced by the three different types of stress—tensile stress, compressive stress and shear stress. The bold lines in each of these drawings represent the shape of the original object, while the dotted lines indicate the shape changes produced by the stress.

So those two units that look precariously balanced are not,' he says. (Figure 1.1 reveals the positioning of the stainless steel rod inside the sculpture.) *Glorious Beauty* is also bolted and resin bonded to three stainless steel blocks (see figure 2.2 (b)) that are welded to a buried stainless steel base plate.

Physics calculations do not only play a role in fixing Simon's sculptures. To create *Unity*, Simon says he needed to consult the engineer he regularly works with to gain a thorough understanding of the thermal expansion properties of the materials used and how they would operate together. (See box 2.2 for more on thermal expansion.)

Although at first glance they appear to be touching, he explains that the granite half and cast polyurethane resin half of *Unity* had to be installed such that a 10 mm gap was left at the closest part 'to allow the resin to expand and contract throughout the day on hot days and cool evenings'. Because the resin expands by around 0.25% over 20 °C, without the gap 'the daily 1 cm expansion would cause the middle part of the sculpture to gradually wear away,' says Simon. He also needed to take the thermal properties of the resin into account while creating *Unity*, as he explains. 'This resin shrinks by approximately 2% while it cures so I took a cast of the stone form then built this up with modelling wax to give an oversized mould for the resin so that when it shrank it matched.'

2.3 Machining sculptures from steel

When starting a new commission the first step for sculptor Juanjo Novella is to create a reduced-size model of the finished steel sculpture. 'My approach to projects is always through models rather than drawings. These models are created from the same material as the final sculpture, which is machine-cut steel. Developing a project directly from models allows me to be involved with the project from a sculptural sense, meaning that I am working with physical things, spaces, and actual concepts, not only with ideas. Also, by using the same material and shape on models you can best anticipate any kinds of issues that could arise on the real-life large sculpture,' says Juanjo, whose public sculptures include *Welcome to my Safe Home, to my Sheltered Haven* in Nelson, New Zealand (see figure 2.4(a)), *Durango* in Abu Dhabi

Box 2.2. Thermal expansion

It is not just sculptors who have to allow for solids expanding and contracting as their temperature alters. Architects and designers need to take expansion and contraction into account when they design any construction or object that will be exposed to a range of different temperatures. For instance, the arch of Sydney Harbour Bridge in Australia can become 18 cm higher on a really hot day, so this change must be allowed for.

For a reasonably wide range of temperatures, if a solid rod is heated the resulting increase in its length is proportional to the increase in temperature. This relationship is shown mathematically in the following equation

$$\frac{\Delta l}{l_0} = \alpha_l \Delta T \tag{2.2}$$

where l_0 is the length of the rod before it is heated, Δl is the change in its length, ΔT is the change in temperature and α_l is the 'linear coefficient of thermal expansion' for whatever material the rod is made from.

Table 2.1 shows the value of the linear expansion coefficient for a variety of solids. α_l increases as the temperature rises, and table 2.1 shows the room temperature values. When making any object, including a sculpture, from two or more different materials it is best to choose materials that have similar thermal expansion properties. This is because different rates and amounts of thermal expansion in the different materials will produce mechanical stresses that can cause damage to the object.

Table 2.1. The room temperature linear thermal expansion coefficient, α_l, for a selection of solids.

Material	Linear coefficient of thermal expansion, $\alpha_l \times 10^{-5}(K^{-1})$
Polyethylene (low density)	18–40
Aluminium	2.39
Silver	1.89
Brass	1.8
Copper	1.7
Iron	1.17
Glass (pyrex)	0.32
Quartz	0.05

Equation (2.2) can be adapted to represent the changes in volume that occur when a solid expands by replacing the initial length and the change in length by initial volume and change in volume respectively, and α_l by α_v which is the 'volume coefficient of thermal expansion'. For a lot of materials α_v has a different value along different directions in the material.

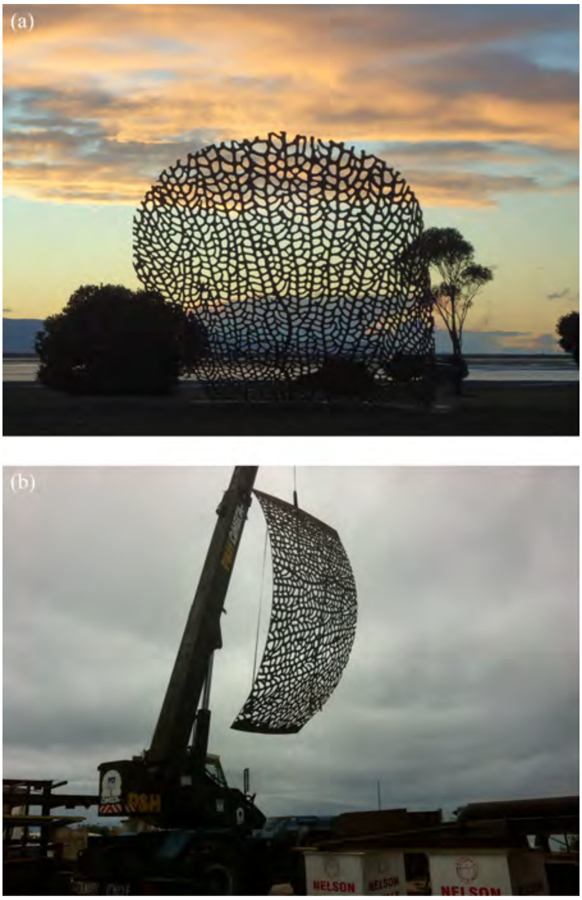

Figure 2.4. *Welcome to my Safe Home, to my Sheltered Haven* by Juanjo Novella. (a) the sculpture *in situ* in Nelson, New Zealand; (b) part of the sculpture being worked on in New Zealand. (© Juanjo Novella. Reproduced with permission.)

in the United Arab Emirates (see figure 2.5(a)), and *Stream* in Phoenix, Arizona in the USA (see figure 2.6(a) and (b)).

To bring a model to life, Juanjo hand draws both the pattern that will be cut out and the overall shape of the finished work after familiarising himself with the shape of the intended art site, and the daily light patterns and human activity there. He then translates this drawing into a computer file that programs a laser cutting machine to precisely cut out a model of the sculpture from a piece of steel. (See box 2.3 for an explanation of how lasers work.)

This manufacturing process is an example of CNC (Computer Numerical Control) machining, as is the cutting of the final sculpture. Rather than being laser cut, this is cut by a flame cutting machine controlled via a scaled-up version of

Figure 2.5. *Durango* by Juanjo Novella. (a) the sculpture *in situ* in Abu Dhabi in the United Arab Emirates; (b) *Durango* being bent into its final shape; (c) *Durango* being installed at its site. (© Juanjo Novella. Reproduced with permission.)

the same computer file that enabled creation of the model. (Figure 2.8 shows the flame cutting of the pattern on one of Juanjo's sculptures.) 'Due to the intricate shape of my pieces and the dependence on cutting machines, I developed, in conjunction with a workshop, a customized cutting program to keep the raw material cold enough to avoid deforming,' says Juanjo, who is based in the Basque-Country.

Once the pattern has been cut in, the steel plates are bent into the overall shape required for the sculpture. (Figure 2.5 (b) shows *Durango* being bent into its final shape.) 'Due to the large size of my work, all these procedures need to be done in the industrial realm. I need large facilities, special machines, cranes every moment, and highly qualified workers,' he says, adding that he often uses navy workshops as they

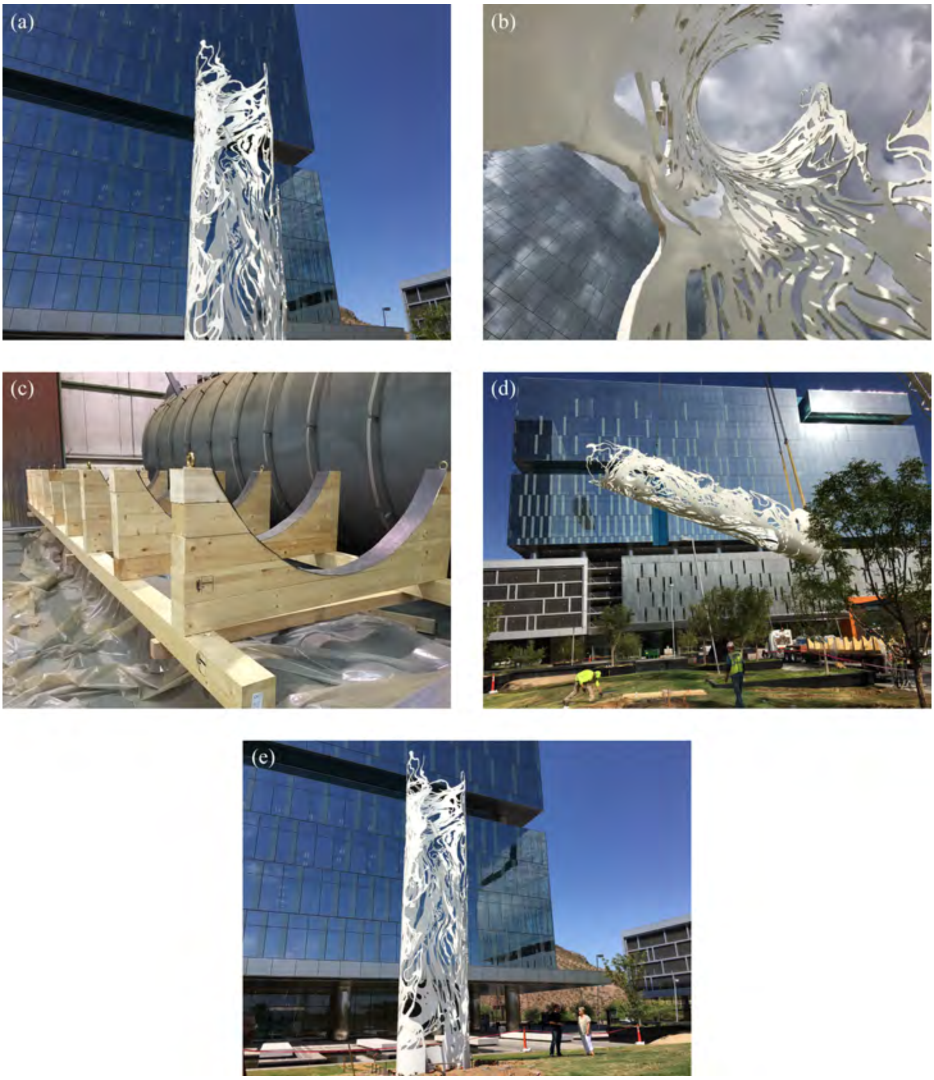

Figure 2.6. *Stream* by Juanjo Novella. (a) and (b) the completed sculpture *in situ* in Phoenix, Arizona in the USA; (c) part of the support structure used for shipping *Stream* to the US from Spain; (d) and (e) installing the sculpture at the art site. (© Juanjo Novella. Reproduced with permission.)

have the heavy industrial equipment and expertise required to create his sculptures. (See figure 2.9.)

This does not mean that the sculptures are always completed before being transported to their sites. 'My last piece, *Stream*, was done completely in Spain then installed in Arizona, [(see figure 2.6(c)–(e))] but this is not regular. What I usually send are parts, and once they are at the destination we proceed with shaping,

Box 2.3. Lasers

All types of laser—including the gas lasers used for laser cutting, and the semiconductor lasers used in laser line generators (see box 2.4)—emit a narrow 'monochromatic' beam of light, in other words a beam of just one single wavelength of light. In this beam all the light waves are 'in phase', which means they are lined up with one another such that the peaks of all the waves coincide. (See box 4.2 for more on the basic properties of waves.)

Laser beams are produced thanks to a process known as stimulated emission. In fact the word laser, which was coined when they were developed in the 1960s, is an acronym standing for 'Light Amplification by Stimulated Emission of Radiation'.

Stimulated emission is one of three basic processes that can occur between a photon (particle of light) and an electron, the other processes being spontaneous emission and absorption. Figure 2.7 illustrates these three processes. Electrons can have different values of energy, E, and the level marked E_1 in the diagram has a lower energy than that of the level marked E_2. If light made up from photons with an energy value equal to the difference between these energy levels (i.e. $E_2 - E_1$) is shone at the hypothetical system shown in this diagram, these photons will be absorbed by the electrons in level E_1. This gives the electrons extra energy, allowing them to move up into the higher energy level E_2 as indicated in figure 2.7(a).

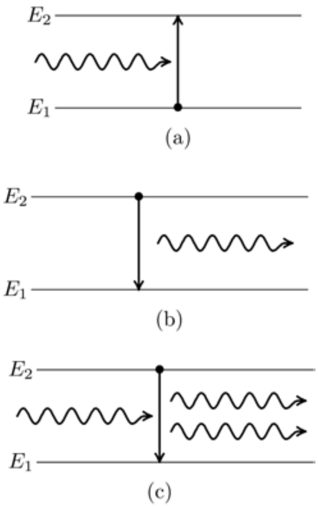

Figure 2.7. The three basic processes that can occur between an electron and a photon. Part (a) shows absorption, (b) spontaneous emission, and (c) stimulated emission. (Adapted from figure 5.2 page 137 of Quantum Mechanics, Foundations and Applications by D G Swanson © 2007 Taylor & Francis Group, LLC. Reproduced with permission of Taylor and Francis Group LLC Books, a division of Informa plc.)

Since electrons will always tend towards being in the lowest energy state possible, a short while after absorption has occurred, an electron that has moved up into energy level E_2 will drop back down into the lower energy level E_1 emitting a photon in the process, as shown in figure 2.7(b). As this process happens without any prompting from outside, it is known as spontaneous emission.

For a laser, you need to induce the final process illustrated in figure 2.7(c), stimulated emission. In this case a photon with energy $E_2 - E_1$ falls on the hypothetical system while an electron is in the energy level E_2. Rather than being absorbed, this photon causes the electron in E_2 to drop immediately back down to E_1 and so emit a photon with an energy value equal to $E_2 - E_1$.

As the photon that stimulated the electron to drop was not absorbed, two photons will be emitted, as indicated in figure 2.7(c). A situation known as a 'population inversion' can be induced in laser systems, in which there are lots of electrons available in the higher energy level E_2 to drop back down to E_1 and emit photons. Under this condition the light falling on the system will be amplified since every photon entering causes two photons to leave. The photons exiting the system are all travelling in the same direction and are in phase with one another as well as having the same wavelength and frequency (see box 4.2), so stimulated emission can produce a laser beam.

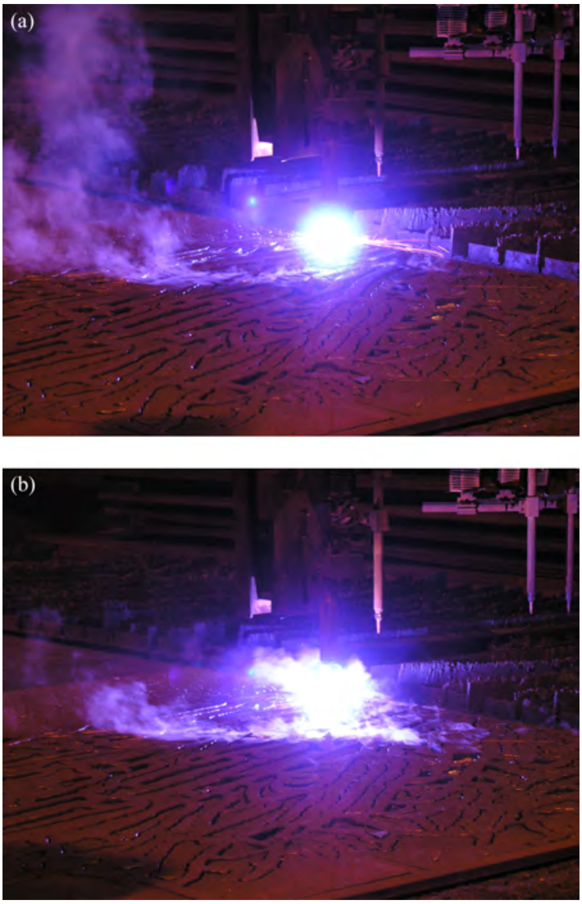

Figure 2.8. (a) and (b) Flame cutting of the pattern on one of Juanjo Novella's sculptures. (© Juanjo Novella. Reproduced with permission.)

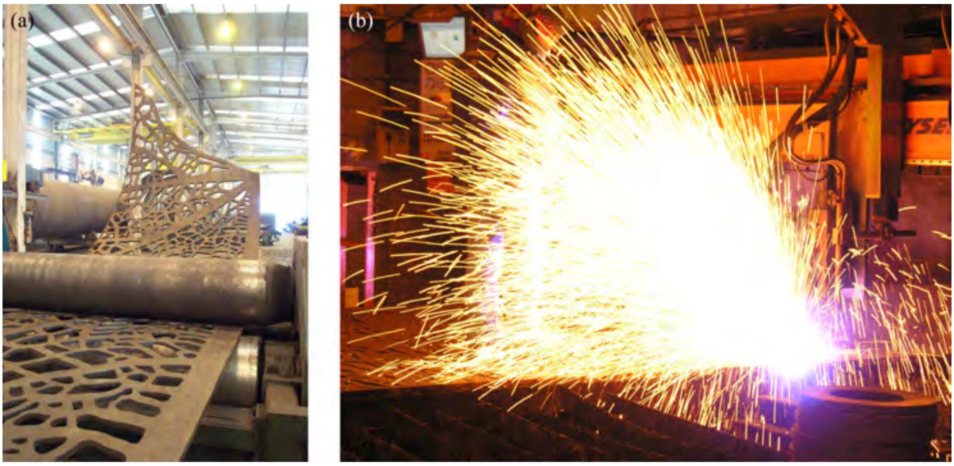

Figure 2.9. (a) and (b) Juanjo Novella relies on the expertise of heavy industrial workshops to make his sculptures. (© Juanjo Novella. Reproduced with permission.)

assembling and installation,' explains Juanjo, who oversees each step of the process in person. *Welcome to my Safe Home, to my Sheltered Haven* for instance was made 'in two big parts. They were cut in Spain and shipped to Nelson. Once in Nelson a local workshop carried out the bending required, and welded both pieces together before grinding and sanding the sculpture and transporting it to the art site. The same workshop also helped us with the installation,' he says. (See figure 2.4(b).)

Juanjo's sculptures are often transported abroad by sea, but can also be flown to their final destination. 'In both cases you have to build a special box adapted to the sculpture to transport it,' he explains. (Figure 2.6(c) shows part of the support structure used for shipping *Stream* to the United States from Spain.)

Once at the art site, his sculptures are securely fixed to the ground by welding them to a steel plate which is embedded in a concrete footing. The depth of this footing depends on the size of the sculpture, and is 'always underground as my favourite way to display is to keep everything that is not part of the sculpture hidden. I have done concrete footings 3 meters deep, and others of about half a meter,' explains Juanjo, adding that because his sculptures are made from the same material, there are no problems caused by thermal expansion occurring at different rates in different parts of the sculpture. 'They work with the warm weather as one whole,' he says.

2.4 Sculpting a work in bronze

Sculptor Philip Jackson, who is based in West Sussex in the UK, works almost exclusively in bronze and has had many public commissions over his 40 year career. Recently these have included the *Bomber Command Memorial* in Green Park in London (see figure 2.10(a)), a statue of *Mahatma Gandhi* for Parliament Square in London, and Manchester United's sculpture of *Sir Alex Ferguson*. As with all of Philip's works, these sculptures began their life as a wax maquette. (Figure 2.10(b)

Figure 2.10. The *Bomber Command Memorial* by Philip Jackson. (a) The finished sculpture in situ in Green Park in London. (Image © Sharon Ann Holgate.) (b) Philip working on the wax maquette for the *Bomber Command Memorial*; (c) the stainless steel armature that supported the full-size clay version of one of the airmen. (Images (b) and (c) © Philip Jackson. Reproduced with permission.)

shows Philip working on the maquette for the *Bomber Command Memorial*.) He finds wax a particularly useful material because of the phase changes it exhibits.

‘If you heat wax up it’s a liquid. If you half heat it, it’s a very soft, easy to mould material, and if you let it cool off a bit it becomes firmer like Plasticine. Then if you let it go very cool it's hard enough to scrape [and so sculpt] with a metal tool. You can use every stage it goes through to your advantage,' explains Philip, who says he has gained most of his knowledge of materials by experimenting himself to discover what does and doesn't work.

'There was not a technical tutor at art school. My teaching was very much in the old, classical style and the emphasis wasn't on materials as much as the study of anatomy, animal life, and the proportions of the figure. I learned the art of casting in art school, but only in plaster as they didn't have a foundry. But you pick technical skills up yourself as you go along if you have an enquiring mind,' he says.

These have included developing an inherent feel for how stress (see box 2.1) affects not only the finished sculpture, but the wax model and subsequent clay replica sculpture. 'Every wax maquette has an armature inside it, generally made out of an aluminium alloy which you can buy from a sculptor's supplier. You can bend and twist it to make it into the right shape. Effectively, if you're creating a figurative piece, you are making a little aluminium wire armature like a skeleton, and you add the wax to that,' continues Philip, explaining that with experience he has developed 'an intrinsic feel for weight and stress' which helps him work out the correct size of armature required to stop the model from collapsing.

This ability is equally important for the next stage in the process in which he scales up the design of the finished wax model by sculpting the artwork from clay at full-size. The clay has a stainless steel armature supporting it from the inside, which in some cases—as with some wax maquettes—also extends onto the outside too. 'If you're doing a figure in wax, the weak points are in exactly the same places as they will be on the big sculpture. So if you've got a figure with thin ankles standing upright, the weakest points will probably be at the ankles and you will need to have an external brace to hold the wax maquette while you're working on it. You look at every sculpture individually and say "where is the weak point?, where is the stress going to be, and where if anywhere is the bend going to be?" then you take measures to counteract that,' explains Philip. (Figure 2.10(c) shows the stainless steel armature that supported the full-size clay replica of one of the airmen of the *Bomber Command Memorial*.)

Philip decided to become a sculptor when he was 11, after falling in love with the ancient Greek and Roman sculptures he saw in a book belonging to an elderly Aunt. 'One of the things that has always appealed to me about sculpture is that it has got a fourth dimension. The Greco–Roman sculptures I had first been entranced by as a boy were 1000 years old and are as good today as the day they were done. I find that side of it extraordinarily appealing,' says Philip, pointing out that many of the tools and materials he uses would be familiar to Michelangelo.

However Philip does employ some modern physics-based technology as he uses a construction-industry laser line generator (see box 2.4 on semiconductor lasers) to make sure that his finished sculptures—which are cast in several pieces—are correctly aligned when they are welded together. He marks the position of laser lines that visually divide up the clay replica into four quadrants by inserting domed head screws into the clay. 'When the bronze casting is done those screw heads show up…and that allows us to check that the sculpture is in exactly the right alignment, as it was in the clay,' he says.

Box 2.4. Semiconductor lasers

Semiconductor lasers (also known as diode lasers) are much smaller than other forms of laser—generally only around 0.1 mm long. This enables them to be used in a range of familiar devices such as CD players, DVD recorders, laser printers, laser pointers, and laser line generators, as well as in telecommunications to send data encoded as pulses of light down optical fibres. As silicon is unable to produce the photons (particles of light) required for forming a laser beam, semiconductor lasers are generally made out of gallium arsenide (GaAs) and its alloys.

In terms of the simplified system of energy levels described in box 2.3 and shown in figure 2.7, inside a semiconductor a lot more electrons will normally be in the lower energy level E_1 than in E_2. However, light with an energy value equal to $E_2 - E_1$ falling on the semiconductor will be absorbed by these electrons, causing each electron to move up to level E_2 and leave behind an unoccupied energy state in E_1 known as a 'hole'. A hole can be thought of as a particle with a positive electric charge the same size as the negative electric charge on an electron. Holes can contribute to the flow of electric current in a semiconductor by moving along in the opposite direction to electrons.

When an electron in a semiconductor falls back from energy level E_2 to level E_1 as a result of either spontaneous or stimulated emission it will recombine (join together) with a hole and give out a photon with an energy value equal to $E_2 - E_1$ as shown in figure 2.7(b) and (c).

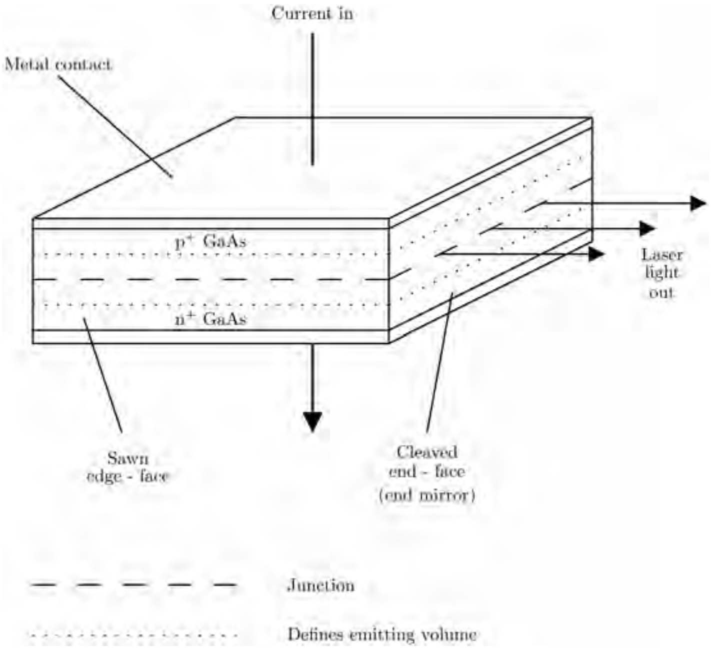

Figure 2.11. Schematic diagram of a gallium arsenide (GaAs) semiconductor laser. (This diagram is copied from figure 10.6 page 232 of Introductory Semiconductor Device Physics by Greg Parker, © IOP Publishing Ltd, 2004. Reproduced with permission of Taylor and Francis Group LLC Books, a division of Informa plc.)

The main parts of a semiconductor laser are shown in figure 2.11. It is based on a p–n junction, which consists of a layer of p-type semiconductor sandwiched next to a layer of n-type semiconductor. Both p-type and n-type semiconductors are created by deliberately adding atoms of another material to the semiconductor in a process known as doping. If the dopant atoms contain less electrons than those of the semiconductor they are going into, this creates positively charged holes and produces a p-type semiconductor that conducts electricity via positively charged holes. Conversely if the dopant atoms contain more electrons than the atoms of the host semiconductor, an n-type semiconductor is created that conducts electricity via negatively charged electrons.

A population inversion (see box 2.3) is created in a narrow area either side of the junction called the 'active region' (indicated by the dotted lines in figure 2.11) by heavily doping both the n and p materials (indicated by the '+' superscripts in figure 2.11), and applying a large electric current. When the large numbers of electrons and holes in this active region recombine they emit photons. These photons can be absorbed by electrons with low energies, or prompt stimulated emission from electrons with higher energies. When the quantity of electrons and holes being moved by the applied current across the p–n junction reaches a certain value, stimulated emission exceeds absorption and so a laser beam can be produced.

Semiconductor lasers have two 'mirrored' ends that are created by splitting or 'cleaving' the semiconductor crystal along a plane of its atoms a bit like splitting wood along the grain. These ends can reflect some of the light emitted via stimulated emission in the device, and every reflected photon can pass back through the active region of the device triggering more stimulated emission. The ends behave like mirrors because their refractive index (a measure of the ability to bend light) is different to that of the air surrounding it. Any light that is not reflected escapes out from the device to form the laser beam.

Once the screws have been inserted into the clay replica, 'we make the first generation mould out of silicone rubber,' says Philip, explaining that he begins by covering the clay with silicone rubber and allowing it to harden. The silicone rubber is then covered in a layer of fibreglass (see box 2.5) that holds the rubber mould in the correct shape once it is taken off the clay replica. The final step for Philip prior to the casting is to cut up the mould—which remains supported by its hard jacket—into separate sections before sending them off to a foundry.

Box 2.5. Composites

The two or more materials that make up a composite provide a combination of properties not available from any single material. Some of the most common examples of composites include reinforced concrete—which is widely used by the building industry and has steel rods embedded in it to make the concrete much stronger when it is stretched—and fibreglass. Fibreglass is as its name suggests made from glass fibres embedded in resin, and has many different applications including being used to make parts of yachts and high performance cars.

As well as overseeing several stages of the bronze casting, Philip also assists with the installation of his sculptures, which are all packed with stainless steel support rods that extend into the concrete or stone base to enable them to withstand stresses including people climbing on them. Once a sculpture has been transported to its site, the installation team carries out ‘a trial lift by crane to make sure the sculpture fits exactly on its base and that there aren’t any gaps between the bronze and the stone. We then put stainless steel rag bolts into the bottom of the sculpture, and the holes in the base are filled with an epoxy grout,’ says Philip, adding that the penultimate step is to lower the sculpture into place such that the stainless steel bolts descend into the epoxy-filled holes. Half an hour later, the glue has cured, and the sculpture is permanently fixed at its site.

2.5 Casting a bronze sculpture

Sarah Craske, artist and founding director of SPACER in Kent in the UK, sees artists delivering their work in various ways. ‘Traditionally you would receive a maquette, and we still get artworks that are delivered in clay or other materials, or works created from ready-made objects. But we are also starting to receive computer files of virtual 3D objects that have been designed in CAD software,’ says Sarah. SPACER’s first step is to make rubber moulds either from the object created by the artist, or from a polystyrene foam sculpture that is machine cut via a 3D computer file supplied by the artist or after carrying out a laser scan of a maquette then digitally scaling it up.

Whether created by a sculptor or a foundry, all rubber moulds must be encased in a rigid material to retain their shape. Sarah explains that while generally a resin is used—which is brushed onto the rubber mould then allowed to harden—as part of SPACER’s commitment to sustainability, their foundry is instead using an eco-product called jesmonite. Unlike the previously used resins, jesmonite is not toxic, which removes the need for as much protective clothing and makes the working environment easier explains artist Stephen Melton, co-owner of SPACER, who is hoping to introduce more eco-friendly materials into their processing in the future.

Once the rubber mould is ready, it is used to cast a 5 mm thick wax replica (see figure 2.12(a)) of the sculpture, explains Stephen, adding that SPACER casts architectural features such as colonnades in non-ferrous metals, and bespoke furniture, as well as bronze and aluminium artworks. The next step in the so-called lost wax process is to ‘envelop the wax in heat resistant materials [SPACER uses plasters and a powdered ceramic called “grog” (see figure 2.12(b))] before melting the wax out to form a cavity by baking in a kiln. Bronze is then poured into the cavity where the wax was, hence “lost wax”,’ says Stephen. (Figure 2.12 (c) shows liquid bronze being poured.) These steps in the process are quite lengthy, as Stephen explains. ‘If we were to use a standard head as an example, to make the rubber mould is usually about a day’s work, and to make a wax takes about a couple of hours. To ‘invest’ the wax—which is the name used for enveloping in heat resistant materials—might only take an hour or an hour and a half, if you’re using the traditional methods that we employ here,’ he says.

Before encasing it in plasters and grog, Sarah and Stephen attach wax rods to the wax replica. These will create channels for pouring the molten bronze in (called ‘runners’) and for allowing air to escape during pouring (‘risers’). The furnaces they

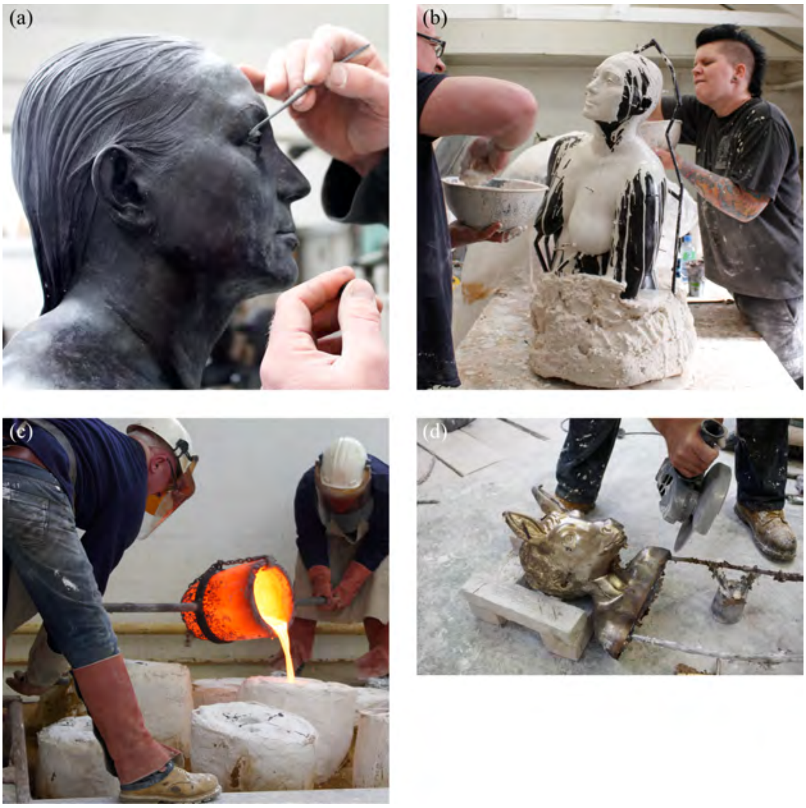

Figure 2.12. (a) Working on the wax replica of *Folkestone Mermaid* by Cornelia Parker; (b) encasing the wax replica of *Folkestone Mermaid* by Cornelia Parker in plasters and grog; (c) pouring liquid bronze; (d) angle grinding off runners and risers from *All I Want Can Only Be Accomplished By Ignoring What You Need*, by Charming Baker. (© Sarah Craske. Reproduced with permission.)

use to melt the bronze are powered by gas from a green gas supplier Eco-tricity who, explains Sarah, also provide the electricity for SPACER's fleet of electric vehicles.

When the bronze is cold, Sarah and Stephen remove the plaster and grog by jet washing, and set the washed-off grog to one side for recycling. They then weld separate sections of the sculpture together, and angle grind off any bronze that collected in the runners and risers (see figure 2.12(d)), and also any marks they have left, or protrusions from welded joints if the sculpture has been cast in several pieces.

'You don't want the welds to show in the final work, so the welding rods must match the bronze we're using,' says Sarah. This ensures the sculpture remains the same colour everywhere after the final step in its creation—applying the patina—occurs. 'If you don't match it, you can make the surface look perfect but when we then do the patination if there's a different material mix in that weld it will colour differently than the rest of the bronze. So you have to make sure that the alloys that you are using are pretty much the same alloys so that the chemical reactions that they take on during the patination process are roughly the same,' she explains. (See box 2.6 for more on alloys.)

Box 2.6. Alloys

Pure metals are too soft for certain applications, and are not particularly easy to machine. However if two or more metals, and sometimes also non-metallic elements, are mixed together, an alloy is formed that has a combination of the properties of its constituents. Alloys can therefore be created with properties tailored for specific uses. For example, stainless steel, which must not rust, contains chromium to improve the corrosion resistance of the steel, which is an alloy itself predominantly made from iron and the non-metallic element carbon. Other commonly used alloys include brass which is mainly made up from copper and zinc, and bronze whose main constituents are copper and tin. While many alloys are created artificially for specific applications, alloys do exist in nature. For instance iron–nickel alloys can be found in some types of meteorite.

The patina is the final surface finish of a bronze sculpture, and while Sarah says foundries often keep their formulae for patination chemicals a secret, she is willing to reveal that ferric nitrate painted onto the bronze after it has been shot blasted with aluminium oxide gives the traditional brown bronze colour. ‘The shot blasting puts a very fine texture on the surface and allows the patina to settle in an even fashion,’ explains Stephen, adding that while some patinas are added cold, others are painted on while heating the bronze with a propane torch to catalyse the reaction. Finally they apply a layer of acid-free wax to seal in the colour, and also protect the sculpture against dirt and the weather.

2.6 Creating sculptures from bronze resin

On some occasions, such as when sculptures are created for temporary public exhibits, it is neither practical nor cost effective to install bronze works. In these cases bronze resin can provide an alternative, as Jonathan Hateley, a UK based sculptor explains. He cast his *All From One* sculpture—which formed part of RHS Garden Wisley’s 2014 sculpture trail (see figure 2.13(a))—from bronze resin in his studio. The first step, he says, was to sculpt the work in clay. ‘For smaller sculptures, particularly if I’m doing them for TV, I tend to use plastiline which is a wax and oil based clay that doesn’t dry out and is good for detail. But for a lot of my work which I exhibit I tend to use normal clay,’ says Jonathan. This must be kept moist at all times by spraying it with water, and covering it overnight with a water soaked cloth and plastic bags.

To support his clay sculptures, Jonathan creates an armature, (see figure 2.13(b)) the main struts of which are made from 1 cm thick steel. ‘You bend that to the shape you want using a vice, and do welds where you need them. For more detailed sections of the sculptures, such as hands, I use an aluminium wire that I can bend by hand. I learned [how to create armatures] after working in the theatre, TV, and for model making companies. In that environment generally there is someone who will make your armature for you and I learned over time what I needed [to do] from what they made for me,’ he says.

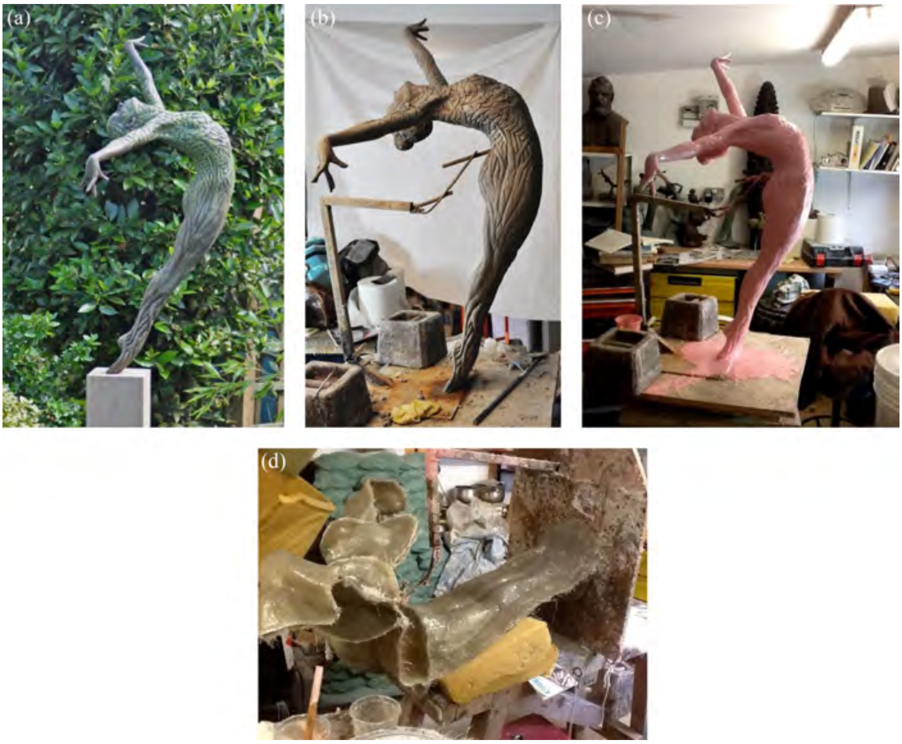

Figure 2.13. *All From One* by Jonathan Hateley (a) the finished artwork on display as part of RHS Garden Wisley's 2014 sculpture trail; (b) the clay version of the sculpture showing the external part of the armature supporting the clay; (c) the silicone rubber applied over the clay sculpture; (d) the discarded fibreglass jacket. (© Jonathan Hateley. Reproduced with permission.)

Once the clay sculpture is completed, Jonathan makes a mould that the finished sculpture will be cast from. To form the mould, the front and back of the clay sculpture is painted with a silicone rubber, and built up into a layer around 5 mm thick (see figure 2.13(c)). The silicone rubber needs to be supported via a fibreglass jacket (see figure 2.13(d)), so a polyester resin is painted over the rubber layer. To create the fibreglass jacket, 'you dab your brush full of resin onto strands of glass fibre mat,' he explains.

'Sculptures can have a number of parts to the mould that depends on how complicated the sculpture is. In the simplest way if the sculpture is spilt into two—a front and a back—you have to create a wall in clay around the sculpture,' continues Jonathan, who makes his moulds in two halves by attaching a wall to the outside of the sculpture that lies in an imaginary plane cutting through the sculpture, and looks like the lip on a jelly mould. The silicone rubber is applied to the first half and also the wall then once this sets, the fibreglass is applied and the wall is removed. He then uses a chemical known as a release agent to cover the join between the two halves and a slight overlap into the front so that when the silicone rubber is applied to the back it does not just glue the two halves together. ‘The walls of the mould are drilled with holes when the mould is still on the sculpture so that when it is taken off it can all be bolted back together to form the sculpture,’ says Jonathan.

Once the sections of the mould are completed, he paints the inner surfaces with two layers of polyester resin mixed with powdered bronze. ‘That metal powder falls within the liquid [resin] towards the mould, and sets within the resin. You then build up the thickness. If it is a small sculpture, you would build it up a bit and then fill the whole mould with a less expensive filler mixed with the resin. But a bigger sculpture would be backed up with fibreglass, like the jacket, which adds structure to the piece,’ says Jonathan.

For *All From One* after the bronze resin hardened, he built up the sculpture’s thickness to approximately 4 mm by laminating the interior with layers of resin and fibreglass. A mixture of resin and glass fibre was then used to join the two halves of the mould. Once the join set, he removed the mould to reveal the final sculpture.

‘With this process you end up with seam lines around the sculpture where the joins are, so I had to grind away the surface to get rid of those seams,’ says Jonathan, who produces sculptures in both bronze and bronze resin. He uses diamond, titanium, tungsten carbide, and carbon cutter attachments on a miniature power tool to grind off the seams, and to sculpt back in any details that have been lost after additional bronze resin has been applied to secure the join area. (Box 2.7 explains why diamonds can cut all other materials.)

To enable fixings to be attached, Jonathan leaves an open end at the base of his larger sculptures. For *All from One* he used polyester resin to fix a protruding steel mount inside each leg of the sculpture. As with bronze sculptures, Jonathan says the final step in creating a bronze resin work is to patinate the outer surface then seal the sculpture with wax, and in some cases hand paint it.

Box 2.7. Hardness

Scientifically the hardness of a material is defined as its resistance to being scratched or dented. The hardest naturally occurring substance is diamond, which because of its ability to cut through any material including other diamonds is used for industrial cutting.

The oldest test for measuring hardness was invented in 1812 by the German mineralogist Freidrich Mohs (1773–1839). The relative measure of hardness he invented, known as Mohs scale, consists of ten materials arranged on a scale (see table 2.2) such that each material is able to create a scratch on either itself or on any of the materials with numbers below it, but cannot scratch any of the materials with numbers above its own. So for instance fluorite can scratch calcite, but not apatite, feldspar or any of the other materials with higher numbers than itself.

Table 2.2. Mohs hardness scale. Diamond is the hardest occurring substance in nature, while talc is unable to scratch any of the other materials in this table.

Number	Material
10	Diamond
9	Corundum
8	Topaz
7	Quartz
6	Feldspar
5	Apatite
4	Fluorite
3	Calcite
2	Gypsum
1	Talc

Useful though Mohs scale is for giving a rough indication of how hard a material is, when precise hardness measurements are required mechanical hardness tests need to be carried out. The Brinell hardness test, for example, involves pressing a steel ball into the surface of the material requiring measurement, and calculating the hardness from the surface area of the indentation the ball creates. The Vickers hardness test works in a similar way, but instead of a steel ball uses a pyramid-shaped diamond cone to create the indentation. By contrast in the Rockwell test hardness is calculated from measuring how far a diamond cone or steel ball indenter penetrates the material. Because a slightly different form of deformation is measured by these different tests, there is no straightforward way of converting between the various hardness scales, but the relationship between them can be represented graphically, as in figure 2.14 (comparison of hardness scales) which also shows the hardness ranges of some commonly used materials.

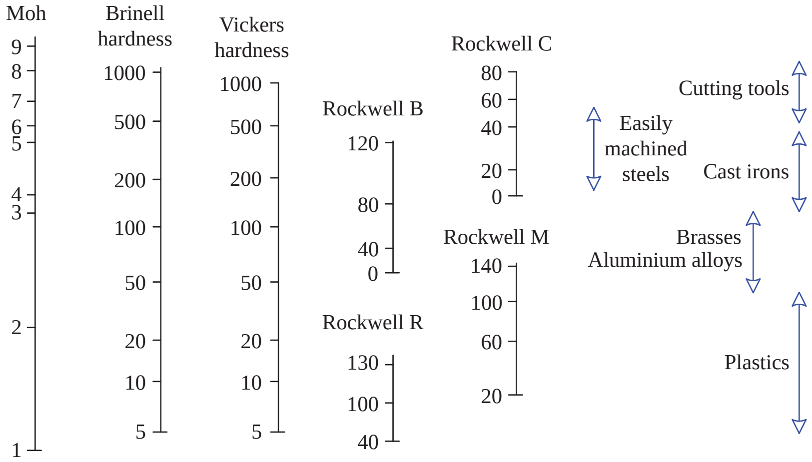

Figure 2.14. Comparison of hardness scales.

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SPACER
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IOP Concise Physics

Outside the Research Lab
Volume 1: Physics in the arts, architecture and design
Sharon Ann Holgate

Chapter 3

Behind the scenes—optics and mechanics in stage lighting and theatrical visual effects

3.1 Introduction

Whether we go to the theatre to see our favourite actors and performers, to hear music we enjoy, to watch a dance company, or to lose ourselves in the story of a play, our experience will be enhanced by physics. From the optics involved in stage lighting to the mechanics that allows scenery changes, for centuries the application of physics to theatrical productions has played a major part in creating spectacles that can wow audiences.

In this chapter we will first look at some of the physics behind the lighting effects that are familiar to today's theatregoers, with the help of Graham McLusky a lighting designer who has worked on theatrical productions around the world for over 30 years. As we will see, lighting technicians use technologies including LEDs and computerised control desks as well as their physics knowledge to help light performances.

Steve Colley, Head of Stage Engineering, Automation and Rigging at the National Theatre in the UK then reveals how physics-based technologies ranging from hydraulic systems and pulleys to electromagnets and touch screen graphics are being used backstage to move scenery and create a range of visual effects.

Finally, thanks to Charlotte Ewart, a dance historian and choreographer I met in 2015 at a Regency dance demonstration, we will also discover what types of visual effects were created for lavish royal dance performances known as masques in the 16th and 17th Century. As this section reveals, while the ability to create some of these effects has been lost to time, the rope-and-pulley-based systems used for suspending scenery were the forerunners of the fly systems we see in theatres today.

3.2 Stage lighting

Even the best theatrical performance will be diminished if the audience cannot see the action very well. As Graham McLusky, a freelance lighting designer who taught

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Figure 3.1. Different stage lighting effects. (a) Working sound panel on the background of the concert stage. (© Epitavi/Shutterstock). (b) Stage lights on a console, smoke. (© Sergei Primakov/Shutterstock.)

university courses in stage lighting at the University of Lincoln in the UK for several years, puts it 'visibility is one of the key objectives. But stage lighting also needs to create a space in which the actors may work that fits with the production in terms of mood and atmosphere,' adds Graham, whose credits include Fame the Musical, and the original production of Buddy which opened in the West End in London, before touring to Canada, San Francisco, and then Broadway. (Figure 3.1 shows two different stage lighting set-ups.)

Skilful changes of lighting can completely alter the mood of a scene, and enhance the audience's ability to read an actor's emotions. The colour, intensity, and positioning of lights all make a difference to the scene. 'For example, take for instance a drama or a thriller such as an Agatha Christie using a box set with a large French window, a door, some furniture, a carpet, and the scene is taking place on a bright sunny day. You need to ensure it looks as though the room is lit by bright sun. So you have to think about what sunlight pouring in through the window would do once it starts hitting the room, and recreate that sort of look and feel,' says Graham. 'Then if the same room is used in another scene set at night, and the characters are talking about how bright the Moon is outside, you will want to light part of the exterior to represent moonlight and perhaps have a degree of moonlight entering the room,' he continues.

Whilst the lighting design aims to look as realistic as possible, sometimes theatrical license has to be taken with the physics of how light falls in order for the audience to follow the action, as Graham explains.

'If you have a scene consisting of a room with a table and two chairs on which there are two actors seated, and one of the characters lights a candle which is the only source of light, you will need to position your lighting so as to create the effect of light being emitted by the candle and falling onto the actors and the surrounding area. [This is known as key light, which in general is the brightest source of stage light that hits an object or area.] So you will need to recreate a similar candlelight colour using appropriate filters, [see box 3.1 on colour temperature] and decide how far into the [stage set] "room" you wish for the light to encroach.'

Box 3.1. Colour temperature

All matter emits electromagnetic radiation, and depending on how hot the matter is it can emit visible light. For instance, the filament of a tungsten bulb emits visible wavelengths when an electric current flows through it, while a hot poker glows when it is taken out of a furnace.

Objects that emit light, such as a candle or a stage light, can be compared via a measure known as the colour temperature with a 'black body'. A black body is a theoretical idealised object which emits a spectrum of radiation solely dependent on its own temperature, and also absorbs all the electromagnetic radiation falling on it. As figure 3.2 reveals, the energy of black body radiation peaks at a particular wavelength, with higher temperatures corresponding to a shorter wavelength for the maximum energy value and vice versa. (See box 4.2 for information on the basic properties of waves.) The colour temperature of any incandescent light source is defined as the temperature on the kelvin scale (K) of a black body that has approximately the same spectral distribution of energy as the light source.

This leads to a useful way of describing different colours of light, particularly when differentiating one type of white light from another. For example, the colour temperature of daylight is around 3000 K at sunrise and sunset, approximately 5500 K at noon on a sunny day, and around 7500 K on an overcast day. Meanwhile candlelight has a colour temperature of 1500 K and a tungsten lamp 3200 K. The colour temperature of stage lights can be changed using colour correction filters that block some of the emitted wavelengths, so giving different effects that can depict particular locations, weather conditions, lighting being used, or times of the day.

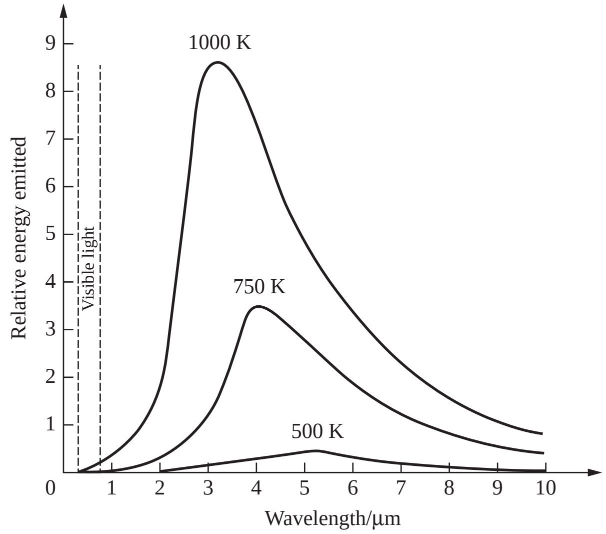

Figure 3.2. Spectra from a black body.

Figure 3.3. Silhouettes of concert crowd in front of bright stage lights. (© dwphotos/Shutterstock).

'For example, if you had a candle in the middle of the stage with two actors sitting each side talking to each other, you could perhaps have a tight pool of light around the actors, focussing the attention on their faces. However, if one of them gets up and walks to the front of the stage then the candle would theoretically be lighting the back of their head. So to keep their face visible to the audience, you may need to

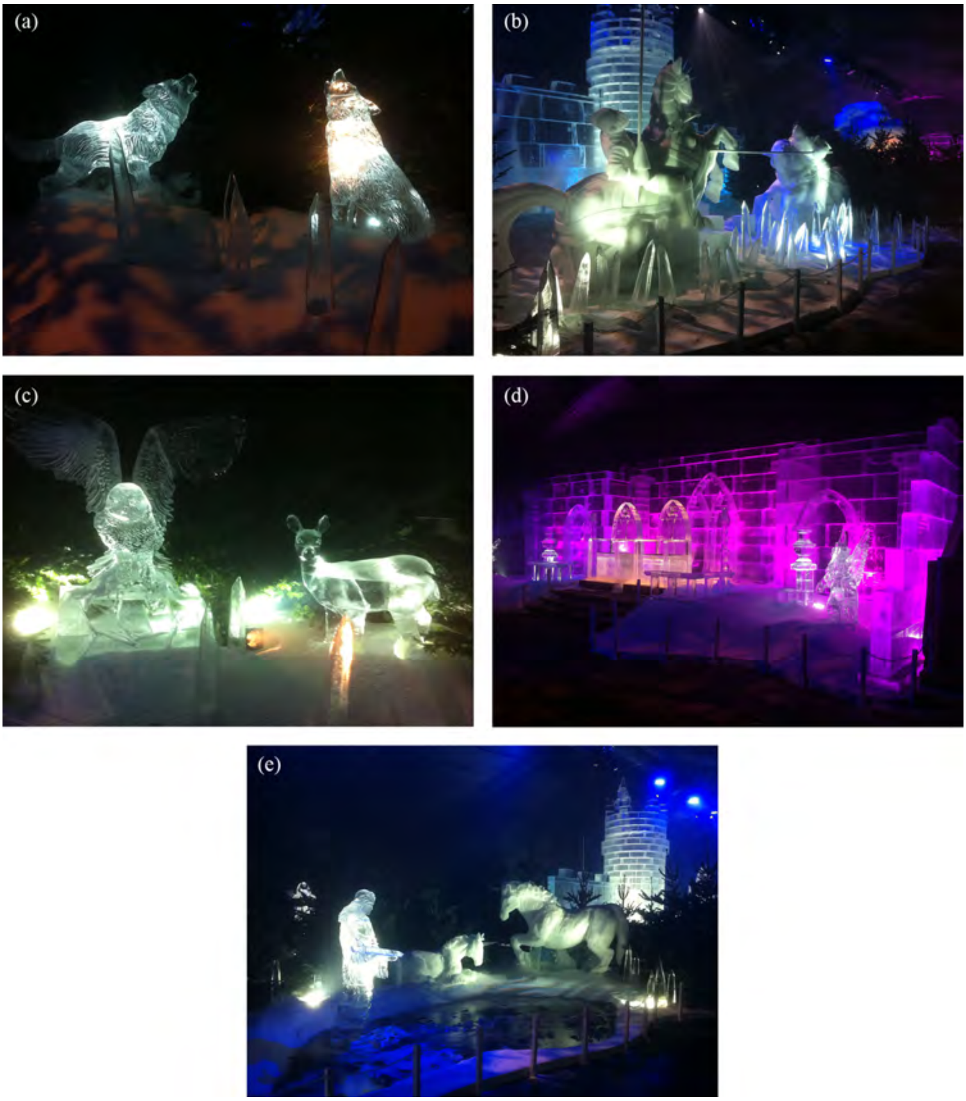

Figure 3.4. (a) through (e) Ice sculptures lit by Graham McLusky at the Winter Wonderland event in 2014 in London. (© Graham McLusky. Reproduced with permission.)

carefully “cheat” some light onto them from the front,’ explains Graham, adding that the audience will accept additional light like this as looking correct even though it is being a bit creative with the laws of physics.

The intensity and angle of lighting is very important in helping to set the tone of a production, continues Graham. ‘Bright light straight on from the front is most useful and effective for comedy, while light from behind can be very dramatic so you see less of the face but more of the back of the head. Lighting from the side can be quite stark and lifts people out from the background.’ So, he adds, side lighting is often used for dance shows as it reveals more of the body form and structure, as well as less of the background and floor.

Choosing to use either the latest LEDs or traditional tungsten light units will make a difference to the overall lighting effect. 'Tungsten light is a very useful light source for the theatre because of the excellent controllability of the filament and the changes of colour temperature when dimmed. For more sensitive theatre productions, I would say that tungsten is more relevant because the fine control is a lot better. But it generates a lot of heat and consumes a large amount of power. Conversely LEDs are great for musicals, concerts, or dance shows as they are incredibly bright and deliver excellent colour with vivid results. [Lighting for a concert is shown in figure 3.3.] You can achieve many effects and fast colour changes which tungsten will never be able to deliver, and they use a relatively small amount of power,' says Graham, who has used white LEDs to light the ice sculptures against a dark background for the Winter Wonderland event in London (see figure 3.4).

Colour filters are used to create different colours from a white tungsten lamp or a white LED light unit. Alternatively 'you may use an RGB (red, green, blue) LED and create a huge spectrum of colours yourself in strong saturated or subtle tones from one (lighting) unit using the appropriate control systems,' says Graham. (Figure 3.5 shows an LED luminaire.)

'However because the combined effect from an RGB mix cannot create a decent "tungsten" white, one requires the help of the additional warm white or amber LED to assist in obtaining that lower colour temperature which tungsten delivers.'

'LEDs have a very different spectrum as compared to tungsten. For example, the cool white and the warm white LED have a much lower red wavelength, so [to mimic the light output of tungsten] a specially adapted colour filter must be used to compensate,' Graham explains. (See box 3.2 for more on colour addition and subtraction.)

Figure 3.5. The SL PAR 155 ZOOM LED PAR luminaire by Philips. (Reproduced with permission from Philips Lighting.)

Box 3.2. Colour addition and subtraction

A primary colour is a colour that cannot be created by mixing together any other colours. While red, blue and yellow are the primary colours of paint, the primary colours of light are red, green and blue. Mixing these three colours of light together in different amounts can produce any other colour light. Equal amounts of all three, for example, produce white light. Red light mixed with an equal amount of green light produces amber yellow, red light mixed with an equal amount of blue light results in magenta, while an equal amount of green and blue light creates a bluish-green called cyan. (See figure 3.6.) When any of the primary colours of light are mixed together to produce other colours this process is known as colour addition.

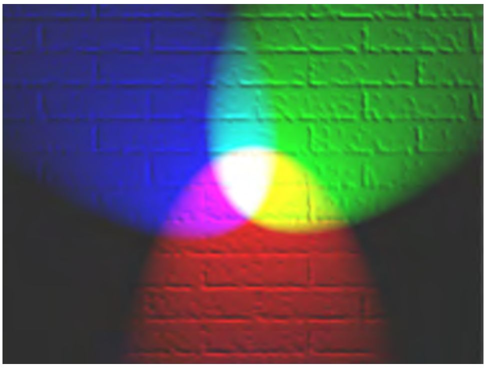

Figure 3.6. Colour addition. Adding equal amounts of the three primary colours of light—red, green and blue—produces white light. (User: Bb3cxv/Wikimedia Commons/https://creativecommons.org/licenses/by-sa/3.0/)

Alternatively if colours are taken away from white light to form other colours, such as by adding a colour filter over a stage light, this process is known as colour subtraction.

Colour can be described in terms of hue, saturation and luminosity. Hue is a measure of the light's wavelength. Saturation can be thought of as a measure of the purity of a colour, and is the amount which a colour departs from white and nears a colour from the spectrum. For example, a pale green light has less saturation than a primary green light. Luminosity is the luminous intensity in a particular direction (see box 3.3 on light intensity).

To create the lighting for a show, 'you have to combine planning scientifically with planning artistically,' says Graham. One methodical way of planning the lighting for each scene is to divide the stage up into a number of areas of the same size that overlap fractionally where they meet. This lighting method was developed by an American stage lighting technician called Stanley McCandless in the 1930s and is still in use today says Graham. 'In theory you could then light each of these areas with up to 6 lighting units. One from the back, one each side, two at 45° from the horizontal and 90° apart, and one straight in from the front to fill up the shadows,' he explains.

‘So now what you’ve got is a stage where you can pick up [with lights] any area, and have several areas on, or half the stage on, and any combination of areas. When you’re lighting, perhaps, a play, you may not wish to have lighting wall to wall, ceiling to floor when there’s a dramatic scene taking place in one particular corner. You may use those areas to pull down [reduce the light in] certain areas of the stage and to emphasise other parts, and you’ve got sufficient lighting to create the mood you require. To help plan brightness and intensity, you may determine the lux levels scientifically and this will assist you in choosing the correct luminaries for the job,’ says Graham. (See box 3.3 on light intensity.)

Box 3.3. Light intensity

In physics, the irradiance is a measure of the concentration of a light’s power, and can be thought of as the amount of light flowing. Irradiance is defined as the radiant flux per unit area reaching a surface. It has the symbol E, and is measured in watts per square metre (W m^{-2}). While irradiance can actually be used to refer to all kinds of electromagnetic radiation, the term illuminance only ever describes visible radiation. Illuminance, in other words the intensity of the illumination, also has the symbol E, (or alternatively E_v) and is measured in units of lux (lx). Meanwhile the luminous intensity, I_v, is a measure of the power of the light emitted from a light source in a particular direction. Its S.I. unit is the candela (cd).

Not surprisingly, irradiance decreases with distance from the source of light. But the decrease in irradiance is not directly proportional to the distance away from the light source. Instead the irradiance a certain distance from a point source of light is proportional to $1/r^2$, where r is the distance away from the light source. This type of relationship is known as an inverse-square law.

In terms of lighting objects on a stage it means that if you position an object 6 m from a light source, for example, it will only be lit a quarter as brightly as if it is positioned 3 m from the light. Figure 3.7 represents the geometry of the inverse square law for a stage light.

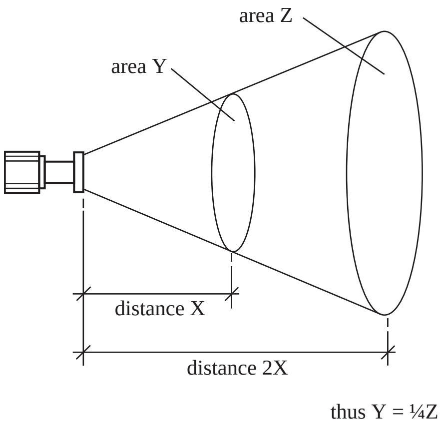

Figure 3.7. The geometry of the inverse square law for a stage light. (From Neil Fraser, Stage Lighting Explained (The Crowood Press Ltd). ISBN 1 86126 490 9. Reproduced with permission.)

Once the lighting for each scene is planned, Graham says you then need to work through the settings for each lighting unit in real time and record them on a computerised lighting control desk. This can subsequently run that sequence of light effects automatically at the press of a button. During the live running of the show, prompts from the stage manager allow the lighting technician to start the appropriate section of saved lighting effects for each scene. ‘However if it is a dance show that is running on recorded music, we can record the lighting for the whole show with a time code sent from the sound department which starts and stops when the music starts and stops. Once you’ve set the lights up, the desk remembers it and the next time you play the music the lights change at exactly the right point,’ says Graham, who used this method when lighting the fast moving Irish dance show Magic of the Dance.

3.3 Theatrical rigging and scenery

Of course lighting is not the only visual effect involving physics that audiences see. The curtain lifting and the movement of backdrops and some other pieces of scenery, for instance, are achieved via a system of ropes and pulleys known as a flying system. (Box 3.4 shows how pulleys enable us to lift heavy loads more easily.) In a simple flying system, each scenic item that needs to be flown is attached to a horizontal metal bar known as a fly bar that is suspended at each end by a thin metal wire ‘flying line’. Each flying line loops over a pulley mounted high above the stage, and joins onto a counterweighted rope that runs vertically down the side of the stage in the wings out of sight of the audience. The rope is held in place by a locking mechanism, which when released enables the fly bar—and therefore whatever is attached to it—to be moved either up or down. (Figure 3.9 shows the main parts of a counterweighted flying system.)

Box 3.4. Pulleys

A pulley is a simple machine that allows a person to raise or lower a load via a belt, chain or rope that runs in the rim of a wheel. In an ideal theoretical system the pulley will be frictionless, and the tension (pulling force) at any point on a single rope running over the pulley will be identical. This means we would not gain any advantage in terms of needing to apply less force using a single pulley to move something heavy. In other words, the mechanical advantage—which is the ratio of the force applied by the system to the force, P, we apply—is one. But a single pulley can make lifting a bit easier by changing the direction in which we need to apply a force to lift a load up.

If several pulleys are linked together in an arrangement known as a block and tackle, see figure 3.8, then we can gain a significant mechanical advantage. This is because each part of the rope in the system will exert the same force that we apply to the end of the rope. So in the system shown in figure 3.8 that contains four pulleys, the net upward force pulling on the load will be four times the force, P, applied by pulling on the end of the rope.

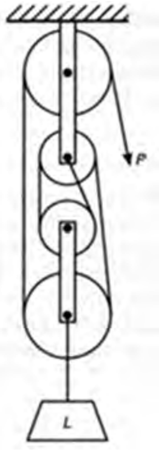

Figure 3.8. A block and tackle system with four pulleys, where P is the force applied by the operator and L is the load. (From A Dictionary of Physics 5th edition (2005). By permission of Oxford University Press. www.oup.com.)

So $L = nP$, where n is the number of supporting ropes, L is the load, and P is the force applied by the operator to the rope. A block and tackle system therefore allows us to lift a much larger load than we could directly.

In terms of its basic operation, this technology has not changed for centuries (see section 3.4 for an insight into 17th Century scenery). However the systems now in use have moved on from manually operated rope and wood, as Steve Colley, Head of Stage Engineering, Automation and Rigging at the National Theatre in the UK—which has three separate theatres; the Olivier, Lyttelton and Dorfman at its London site—reveals.

‘A counterweighted flying system such as we have in the Lyttelton consists of a large counterweight cradle that can hold up to 1000 kg of steel weights, the vertical rail system on which the counterweights are mounted, the steel wire ropes that run from the counterweight to the fly bar, and the operating lines by which the flymen move the counterweights and thus the bars up and down. The systems are loaded by moving the bar to stage level. That allows a flyman to load counterweight from a gallery under the main grid. Load is often then added at fly floor level to balance the piece as required. We have 71 manually operated fly bars in the Lyttelton. In the Olivier we have 60 multi-line winches and 30 single line winches all computer controlled by our programmable system. In addition we have 90 chain hoists and an assortment of manual chain blocks,’ explains Steve, whose team is responsible for most of the mechanical elements of productions and stage infrastructure, including winches and hoists, hydraulic systems, elevators, revolves, and flying systems.

‘We deal extensively with loads and force, momentum, dynamic loading, material elasticity, coefficients of friction, fluid pressure systems and hydraulics, structural steel and aluminium, rotating machines, winches and hoists. So I think it is fair to say that physics plays a large part in most of our daily activities,’ continues Steve,

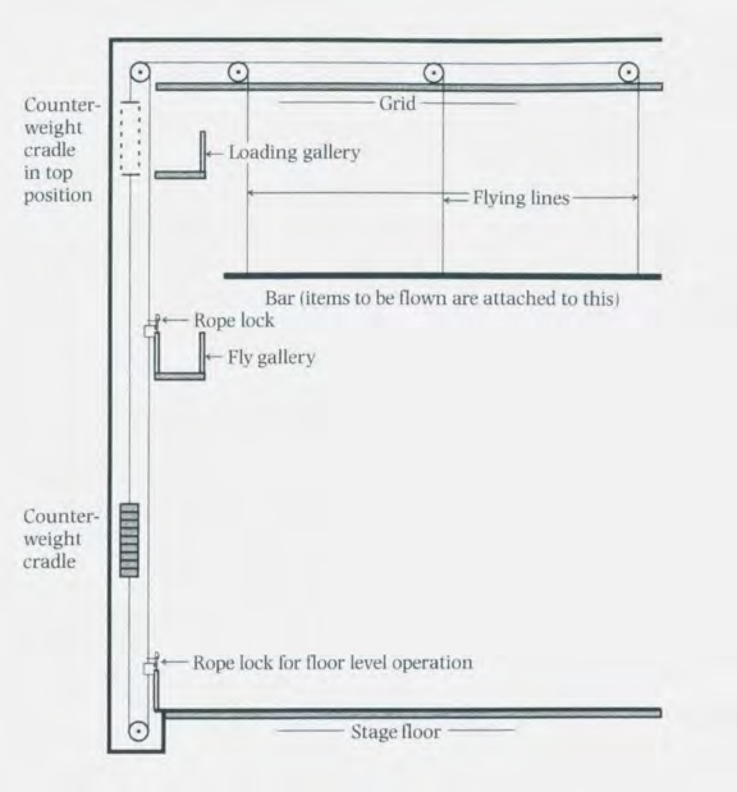

Figure 3.9. The main parts of a counterweighted flying system. (From page 131 of Winslow, Colin (2006) The Handbook of Set Design (The Crowood Press Ltd) ISBN: 1 861268130. Reproduced with permission.)

who has worked in stage engineering for 35 years. Much of his physics knowledge has been gained via vocational training, he says, which has been supplemented by specific training as required. 'I need to have a thorough practical working knowledge of all the systems I deal with apart from the software side of the complex automated control systems we use. I am also involved extensively with our consulting structural and mechanical engineers.'

While a lot of their scenery is flown, various other physics-based methods are used to move scenic items in and out of view of the audience. 'We use remote control for small scenic items. Some productions have larger remote controlled elements, but often larger elements are automated or operated manually. We use rotating shaft or magnetic mechanisms (referred to as a Kabuki drop) to drop scenery and scenic elements remotely from the grid or flown bar or truss and to deploy large fabric screens.'

'A Kabuki drop is a method of causing scenic cloths to fall and be revealed, and often to fall again where the entire cloth ends up on the stage. A simple version holds the container and the cloth on pins secured to a rotating shaft. When the shaft rotates, one side of the container is released allowing the cloth to fall, when the shaft rotates again the cloth itself falls to the stage,' explains Steve. Magnetic mechanisms use an electromagnet (see box 3.5) which is switched on to hold an object out of sight of the audience, and switched off to enable the object to fall to the stage.

Box 3.5. Electromagnets

An electromagnet consists of a cylindrical-shaped coil of wire that an electric current can pass through (see figure 3.10). It may also contain a core made of a 'soft' ferromagnetic material, such as soft iron, in the space between the coils. When a current flows through an electromagnet's coil of wire a magnetic field is produced, the strength of which is increased by the presence of a ferromagnetic core, which becomes magnetized.

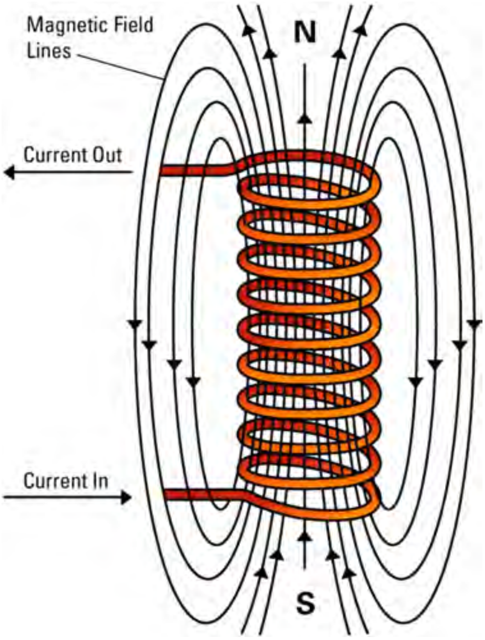

Figure 3.10. An electromagnet. (www.LANL.gov.)

While hard magnetic materials become permanent magnets once they have been magnetized, soft magnetic materials are only magnetized when they are in a magnetic field, and lose their magnetization once the field is removed. So unlike permanent magnets, electromagnets only produce a magnetic field—and so are capable of attracting magnetic materials—while current flows through the coils. When the current is turned off, the core loses its magnetization.

Electromagnets are used for applications in which a magnetic field is not needed all the time. As well as being employed in the theatre to hold objects that later need to drop to the stage, electromagnets are found in a wide range of other settings. For instance, electromagnets read and write data in magnetic recording systems, enable doorbells to ring, are used in industry to lift heavy objects, and help provide the propulsion for Maglev trains.

Periaktoi are another way of changing the scenic background, and are occasionally used by Steve and his team. They consist of a triangular rotatable frame with a different scene mounted on each side. With several periaktoi in a row, one simultaneous rotation of each will produce one scene change, while a second rotation will bring the third scene into view. This method has been used for centuries, including by Inigo Jones (see section 3.4) who designed the scenery for court masques in England in the early 17th Century. ‘Periaktoi are rarely used at NT [the National Theatre] and in the last four years we have used one in the Dorfman. They can be electrically or hydraulically driven by chain or rams. They are often associated with classical productions, and large ballets and opera,’ says Steve.

‘We also use hydraulic systems for temporary lifts, revolves and small elevated platforms,’ he continues. A revolve is a platform for scenery that rotates about a fixed point, and while revolves are often bespoke made for particular productions, some theatres—including the Olivier at the National Theatre—have built-in revolves. ‘The Olivier Drum Revolve is 168 000 kg and contains hydraulic and electrically powered elevators. The whole Drum is a large revolve and there is an integral semi-circular disc revolve on top.’ (See figure 3.11.)

Materials physics also plays an important role backstage at the National Theatre as although some of the scenery is built from timber and steel using traditional construction methods, much of it is created from high tech, heat-resistant materials. ‘The scenery construction often involves lightweight materials, twin wall polycarbonates, Aerolam panels and materials from the aerospace industry, Kevlar, Aramid, and Dyneema, along with carbon fibre products,’ explains Steve.

Figure 3.11. The National Theatre’s production *Treasure Island* and *His Dark Materials* made use of the drum revolve. (Photograph by Philip Carter. © Philip Carter, National Theatre 2015. Reproduced with permission.)

The National Theatre's backstage computer systems, that can be programmed to control some of the scenic effects, are equally pushing at the boundaries of current technology, as Steve reveals. 'Our computerised control systems for the Automation department are world class using bespoke touch screen graphical user interfaces, distributed real-time high speed networks, and state of the art 3D CAD modelling and pre visitations.'

3.4 Behind the masque—visual effects in 17th Century royal productions

As mentioned in the last section, many of the basic principles for the scenery and special effects we see in modern theatrical productions were in use as long ago as the early 1600s. One of the best known stage designers of that period was Inigo Jones, an English architect, who designed elaborate costumes and sets—including pioneering fly systems—for the masques staged in England by King James I and his queen Anne of Denmark, and James' son King Charles I and his queen Henrietta Maria.

As Charlotte Ewart, a dance historian and choreographer specialising in 16th and 17th Century dance explains, masque was an art form that had its origins partly in the small allegorical theatrical performances at the court of King Henry VIII in England, 'but really took off following a grand dance production staged in 1581 in France, called *Le Ballet Comique de la Reine*. It gained popularity in England under the reign of King James I, with Ben Johnson writing many of the texts and Inigo Jones designing many of the sets.' Masque then finished abruptly in the subsequent reign of Charles I with the outbreak of the English Civil War.

It is essentially the forerunner of modern ballet, but unlike today's ballets, the masque was mainly performed by royalty and aristocrats. While some professional dancers took part in the antimasque, which was the first of the three sections of the performance, the subsequent main masque, and the 'revels' which concluded the spectacle were danced by the monarchy and aristocrats. The whole spectacle was designed to show off the splendour and power of the royal family and their courtiers, says Charlotte.

This was a time in which skill on the dance floor was as integral a part of an aristocrat's education as maths and science. Any visiting aristocrat from a foreign court was expected to dance in the revels, and if they were unable to they had to appoint a 'dance proxy' to perform on their behalf. In England, masque performances were in front of a private audience of peers, but in France the masques, known as ballets, could be watched by the public. Perhaps not surprisingly for events involving royalty, the costumes and scenery were lavish. Charlotte says the stage sets and room surroundings were 'an intrinsic part of the audience's experience of masque, alongside the choreography, the music and the performances.'

'These events were huge,' continues Charlotte, who has used contemporary reports written by diplomats and ambassadors, as well as financial accounts that detail expenses for scenery, to help reconstruct parts of the performances and so learn more about masque. 'The Banqueting House [in London], which was a space deliberately built to house these theatrical events, is very big and elaborate. The sets were also very intricate, elaborate, well designed, and experimental. The whole purpose of the masque, certainly in England, was to show off how powerful, and how close to God the king and queen were,' says Charlotte, adding that the 'wow effect' of Jones' sets brought all of these ideas together, and helped 'create an immensely grand sense of majesty'.

Contemporary reports speak of characters in the masques ascending and descending as if to and from the heavens onto the stage, and lighting effects involving torches and candles. 'There was a mesh of culture across Europe at that time and Jones adapted ideas from productions he saw in France, Italy and Spain. He built flats and suspended flies, so you would have flying bits of scenery coming down all operated by ropes and pulleys. [Box 3.4 explains how simple pulleys work.] There was Jupiter descending down from the sky, eagles flying up, there was a time when the Queen descended down as a divine beauty in a chariot on a cloud. This cloud was supported on wires and operated by ropes, which is similar to the technology you will see in theatres today,' Charlotte explains.

'Whilst we will never know exactly what a masque looked like, we do know that the sets were enormous and had flights of stairs leading down to an absolutely vast green baize stage area. I imagine that the dancers for the main masque would come down these flights of stairs onto the huge flat space on which they would perform their intricate weavings and patterns. I think the best modern analogy that we have is a Busby Berkeley musical,' she continues.

Charlotte explored the possibility of recreating some 17th Century technology in 2014 when she worked with Prof Tom Betteridge and Prof James Knowles from Brunel University to restage *Love's Welcome*, an entertainment (short type of masque) from 1634 at Bolsover Castle. She explains that 'a "cloud machine" featured in the original outdoor performance when a pair of cupids "flew" down on a cloud.' So Charlotte and her colleagues used physics to try to work out how this machine enabled two performers dressed as cupids to be flown down on-board wooden clouds, as mentioned in the original Ben Johnson script from 1634.

'We think the performance took place within a walled garden [see figure 3.12 for a plan of Bolsover Castle], and that they used some sort of counterweighted pulley system outside the walls that lowered the performers down. There are no written records or diagrams of how this was done, so we have a theory that the characters came down from inside the castle. But by using physics we worked out that the room [they assumed was used] isn't long enough to build a structure that will be able to lever people down. So we know that can't be right. But we know there was some sort of cantilevered system that had to be wooden, and had to be operated with ropes. We also think that it was a huge structure that used a lot of wood because we know [from contemporary financial accounts] the whole entertainment cost the equivalent of £15 million to build,' explains Charlotte.

She hopes to one day re-stage *Love's Welcome* with a working cloud machine if she can discover how it worked. 'I like to reconstruct performances because I think you can only learn a certain amount from reading. To really find out how things were done you actually have to get up and do it. [In this case] we still haven't solved the mystery, but we're hoping to get an engineer on board to make our cupids fly.'

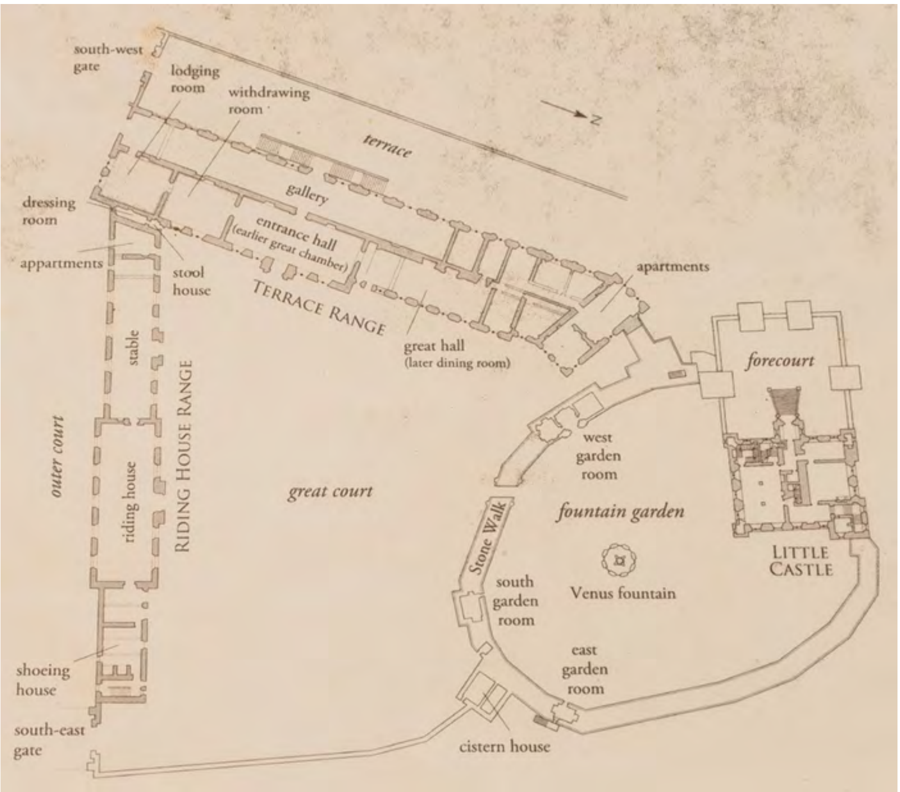

Figure 3.12. A floor plan of Bolsover Castle. (Photograph by Kate Furr-Danner. Reproduced with permission).

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Weblinks

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Daily Mail article from 2014 about Winter Wonderland ice sculptures
The Buddy Holly Story
The National Theatre
English Heritage video of the Bolsover Castle Masque Project
17th Century Theatre section of the V&A website, including information about Inigo Jones and prints of court ballets
Banqueting House in London
Charlotte Ewart's website Dance Thru Time
The Court Masque by Martin Butler, The Cambridge Edition of the Works of Ben Jonson Online
Information about The Court Masque Era and Inigo Jones on the Banqueting House website
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Chapter 4

Sounding good—acoustics and technology in sound recording

4.1 Introduction

It is unlikely most of us give much thought to how sound is recorded when we watch films or TV, or listen to our favourite radio stations. But successfully recording speech and other sounds involves a lot of physics not just in the equipment, but also in working out how best to set up for making a recording.

In this chapter we will learn the factors that need to be taken into account to record crisp, clear sound. We will first hear how sound is captured for speech radio programmes thanks to my friend and colleague Julian Mayers, a TV and radio producer who produced the first programme I presented for BBC Radio 4—a documentary about the Indian physicist S N Bose.

The physics-based equipment and techniques required to capture sound in a range of environments and for different types of production are then revealed by my friend Paul Paragon who has worked as a freelance sound engineer for over 20 years on a wide range of projects including the James Bond film *Skyfall*, TV nature documentaries, and orchestral recordings.

This chapter then concludes with a look at some fundamental research being carried out by physicist Alexey Kimel and colleagues from Radboud University in The Netherlands into a new type of magnetic recording method that could be used for data storage in the future.

4.2 Sound recording for speech-based radio

When capturing sound on location for speech-based radio, the first thing the producer or sound engineer needs to decide is whether the background noise needs to be part of the recording, says producer Julian Mayers, who co-owns the production company Yada Yada. This decision, he says, will depend on the type of interview. ‘If you’re recording in a rainforest you will want to hear the rainforest

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in the background, but if you're interviewing a politician about tax you won't want to hear a lot of traffic noise in the background.'

Julian has worked in broadcasting for over 25 years and originally trained at the BBC as a sound engineer after completing a BSc in physics. 'The BBC were taking graduates from all backgrounds to re-train as engineers, so I applied and in my first two years working there spent about 3 months on their residential training courses,' recalls Julian, who soon opted to become a sound engineer after becoming increasingly interested in programme making. 'Sound can be an extraordinarily creative medium,' he says.

This change in direction meant Julian was sent on a further three specialised courses to learn how to capture the best quality sound. 'There was a lot of physics in that training, as you had to know about sound waves [see box 4.1], and amplitudes and frequencies [see box 4.2], and how different types of microphones work. So I found it really useful having a physics background because to me that was all quite easy [to understand],' he says.

As for TV, the result of sound recording for radio will depend on whether the sound is being captured in a studio, or not, and what background noises need to be minimised. The studio is your 'optimum environment' for sound recording, says Julian, because there is not very much echo coming back from the walls. 'It is set up to hear a voice and an instrument.' This, he explains, is achieved by the walls being covered in materials that absorb most of the sound with minimal reflection back to colour the original voice.

Whether in a studio or on location you must try to get recordings as free from electrical noise produced by the equipment as possible, continues Julian. 'If you record at too low a level you can boost it up afterwards, but you will also boost up all the hisses as well. If you record at too high a level the sound tends to distort,' he explains, adding that nowadays almost all sound recordings are stored digitally on a flash card housed within a small hand-held device if you are recording outdoors, or in a larger device in a studio. (An audio file of Julian recording at the correct level and at too high a level is available as audio file 4.1 from book information at https://doi.org/10.1088/978-1-6817-4469-8. (© Julian Mayers. Included with permission.))

'You also need to aim for as few pops on your recording as possible, and have it covering the entire dynamic range of frequencies,' continues Julian. (Box 4.2

Box 4.1. Sound waves

Sound waves are an example of an elastic wave, which is a wave made up from the vibrations of the particles of whatever solid, liquid, or gas it is travelling through. The vibration passes from one particle to the next particle which then passes it to its neighbouring particle and so on, so that the wave travels onwards. By contrast, electromagnetic waves (sometimes shortened to e-m waves) including light and x-rays, do not disturb the particles of the solid, liquid, or gas they are travelling through. Instead they are comprised of vibrations of the electric and magnetic fields in the area they are moving through. This enables electromagnetic waves to pass through space—which contains so few particles that it can be thought of as a vacuum—unlike sound waves which cannot travel along because there are not enough particles present to pass on the vibration.

Waves can be grouped into two types, longitudinal and transverse. Waves such as sound waves that travel along in the same direction as the vibration that makes up the wave are known as longitudinal waves. Electromagnetic waves are a type of transverse wave which means a wave that moves along at right angles to the direction of motion of the vibrations that it is made from (see figure/video 4.1).

Figure/Video 4.1. Demonstrating the difference between longitudinal and transverse waves using a slinky spring and a skipping rope. To create longitudinal waves with a slinky spring one hand needs to remain still while the other hand is used to repeatedly push on the spring and so generate longitudinal waves that travel along the spring from one coil to the next. To create transverse waves with a skipping rope, one person needs to hold one end of the rope still while the other person moves their hand from side to side to generate transverse waves that travel along the rope towards the still end. (© Sharon Ann Holgate).

The to-and-fro vibrations of the particles of the medium (solid, liquid, or gas) that a sound wave is travelling through change the local pressure of the medium. In regions known as compressions the particles are pushed closer together and the pressure is higher than the normal pressure in the medium. Conversely in rarefactions the particles are farther apart and the pressure is lower. So sound waves are pressure waves, and most of the sound we hear is transmitted by air molecules vibrating and so causing localised changes in air pressure. (The coils of the slinky spring show this effect in figure/video 4.1.) Sound waves are spherical three dimensional waves which spread outwards from their source in a similar way to water waves in a pond after water has been poured in. (See figure/video 4.2.)

Figure/Video 4.2. Ripples on the surface of a pond after water has been poured in. The location of the crests of the waves at a specific moment in time is known as the wavefront. The wavefronts can be seen to spread outwards and expand as they move further away from the source. As the area of the wavefront is increasing, the energy of the wave per unit area is decreasing. Sound behaves in a similar way, with the sound intensity (see box 4.5) decreasing in inverse proportion to the square of the radius of the wavefront. (© Sharon Ann Holgate).

Figure 4.3. A pop shield reduces the air pressure reaching the diaphragm of a microphone when ‘p’ and ‘b’ sounds are spoken. These images show a Zoom H4N recorder which has a microphone at the top as seen in (a) when there is no pop shield in place. Image (b) shows the pop shield over the microphone. (© Julian Mayers. Reproduced with permission).

describes speech frequencies as well as the basic properties of waves.) Placing a pop shield (see figure 4.3) between whoever is speaking and the microphone will reduce the number of pops on a recording. ‘A pop shield stops high, powerful sounds getting

Box 4.2. Basic properties of waves

Figure 4.4(a) shows a sine wave, which can be used to represent both transverse and longitudinal waves. The distance from one peak to the next (or from one trough to the next) is known as the wavelength and is represented by the symbol λ, while the amplitude, A, indicates the maximum extent of the displacement of the vibration from an undisturbed position.

The number of vibrations per unit time is known as the frequency. This can be represented either by the symbol f or by ν(nu), and is measured in units of hertz (Hz). Sound has frequencies between 20 and 20 000 Hz, as these are the frequencies the human ear can hear. Vibrations with a frequency above 20 000 Hz are known as ultrasounds, and can be heard by some animals. Normal speech lies in a frequency range of approximately 400–6000 Hz.

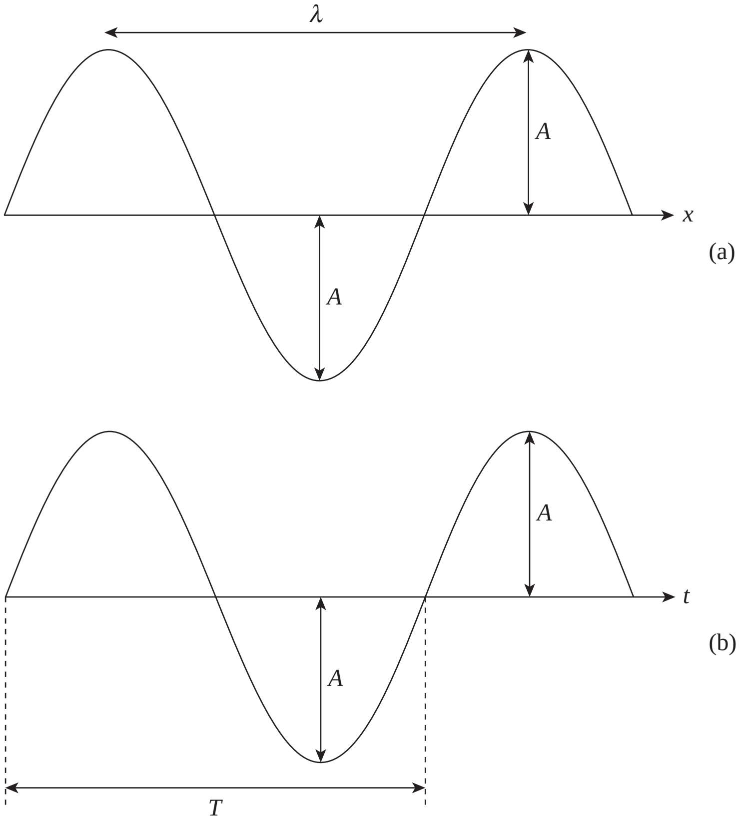

Figure 4.4. Some basic wave properties. λ is the wavelength, A is the amplitude, T is the period, x represents distance, and t is time.

Another commonly used term for describing waves is the period, T (see figure 4.4(b)). This is the time, measured in seconds, s, taken for one complete vibration—in other words, a full movement to and fro of the particles or fields transmitting the wave that finishes back at their starting point. The following equation shows how the period is related to the frequency

$$T = \frac{1}{f} \tag{4.1}$$

In real life, there are lots of different shapes of waves, known as waveforms. The range of other shapes besides that of a sine function includes pulses, sawtooth waves, and square waves. However sine waves are particularly important in physics because a mathematical series of sine waves, known as a Fourier series, can be used to represent all other waveforms.

to the diaphragm of the microphone [which vibrates in response to sound]. "p" and "b" sounds are called plosives, and they will make the diaphragm vibrate to its maximum and produce a horrible distorted popping noise on your recording,' explains Julian. (See box 4.4 for more on how microphones work.)

'If you put your hand up in front of your mouth and make "p" sounds, you can really feel that breath on your hand. On a microphone that pressure is going to make the diaphragm vibrate to its limit. The pop shield filters the air, working like a barrier. It lets the sound go through but it reduces the air pressure hugely on those "p" and "b" sounds. The energy of those plosives is reduced, stopping the input signal from being far too high,' explains Julian. Pop shields can be especially important when recording outside, he adds, as are wind shields. (See later in figure 4.9.) (An audio file of Julian recording with and without a pop shield is available as audio file 4.2 from book information at https://doi.org/10.1088/978-1-6817-4469-8. (© Julian Mayers. Included with permission.))

'A wind shield reduces the energy of the very low frequency sounds which are associated with wind. On a windy day it can completely ruin your recording if you have too much air reaching the microphone,' says Julian. (An audio file of Julian recording with and without a wind shield is available as audio file 4.3 from book information at https://doi.org/10.1088/978-1-6817-4469-8. (© Julian Mayers. Included with permission.))

Normally our brains have a tendency to filter out background noise such as wind and air conditioning systems, continues Julian, so he says wearing headphones (see box 4.3) when recording for broadcast is 'imperative' because it causes us to hear everything. 'You want to hear warts and all exactly what sounds are being recorded,

Box 4.3. Headphones

Transducers are devices that convert energy from one form into another. Both headphones and microphones (see box 4.4) are transducers, with the former converting an electric current into variations in air pressure that we hear as sound, and the latter working in the reverse way converting sound into an electric current.

Headphones (see figure 4.5 for an example of professional spec headphones) are essentially mini speakers. They convert an electrical signal into sound via the same electromagnetic principle that enables electric motors to work—namely a wire carrying an alternating electric current moving thanks to the interaction between the magnetic field created by that current and a nearby magnet.

Figure 4.5. Recording in Studio. (Credit: Masterchief_Productions/Shutterstock.)

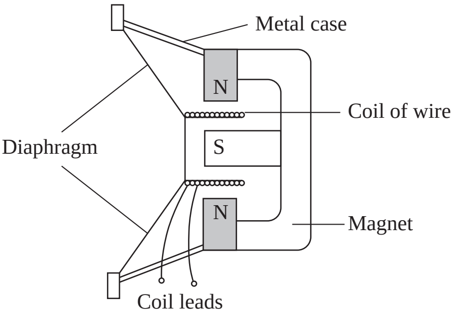

Figure 4.6. A moving coil loudspeaker. This works in exactly the same way as moving-coil headphones, which are often referred to as dynamic headphones.

In the case of headphones, the electric current will come from a device such as a radio, mp3 player, or microphone, and the waveform (see box 4.2) of this alternating current will represent the speech, music, or other sounds. Within each headphone, the current flows through a coil of wire which is surrounded by a magnet (see figure 4.6). As the alternating electric current travels down the wire it creates its own varying magnetic field. This magnetic field will interact with the magnetic field from the permanent magnet, and when the wire has an opposite magnetic pole to that of the surrounding magnet it will be attracted to the magnet and so move closer to it, and when the varying magnetic field has a like pole the wire will be repelled from, and so move further away from, the permanent magnet. As the wire is attached to a moveable diaphragm, this to and fro movement causes the diaphragm to vibrate in accordance with the electrical waveform. The sound waves this moving diaphragm creates have the same frequency as the alternating current and so reproduce the original sound.

and be really aware of the environment you are recording in, so you have chance to change that environment if needs be.' Julian feels his knowledge of physics can be particularly helpful when trying to get the best possible recording on location. 'It is a really good thing to come from a background of knowing how sound works,' he says.

When it comes to choosing a microphone, whatever type you use you need a particularly good frequency response when recording for broadcast explains Julian. 'You ideally want the microphone's response to be as good at 20 Hz as it is at 20 000 Hz. Cheaper microphones won't have a very good frequency response at the higher or lower end [of audible frequencies], but expensive ones will have a good response across the whole frequency range.' Recording speech with cheaper microphones can lead to you losing some of the richer voice tones at the bass frequencies as well as some of the higher tones, he warns.

'Sometimes you do want to turn down a particular frequency, and some microphones will allow you to do this. For example, if there is a background hum you want to record without that hum if possible. Or if there is low frequency wind noise you might want to turn those frequencies down. You're trying to record someone's voice as cleanly as possible given where you are, or you move out from where you are and record somewhere else,' continues Julian.

'Because editing is digital now rather than on tape, to a degree you can tinker around with certain frequencies afterwards by putting in filters that will cut out a particular frequency. For example you could filter out the 50 Hz hum from the electricity mains, and its harmonic overtones [see box 5.3 for an explanation of overtones]. But this makes a difference to the sound of a person's voice so you have to be careful with using filters,' adds Julian.

Whether recording on location or in a studio, the choice of microphone type will be dictated by how many directions you need to record the sound from, says Julian. 'With each microphone you are trying to convert the pressure energy from your voice [which changes the surrounding air pressure] into an electric current. Some microphones will record sound coming from any direction equally,' he explains, while a bi-directional microphone records sounds from the front and behind but not from the side. This is used if you are recording a conversation between two people sitting opposite one another, says Julian.

If you are just recording a single voice in an intimate interview where you want to reduce the amount of external noise coming in from the side, you would use a directional microphone instead he continues. 'You see these quite a lot on video cameras. They are very long, thin microphones which record in a very narrow beam in front of you. If you talk to the side of these microphones it would sound much quieter,' explains Julian. (Box 4.4 describes how some common types of microphone work.)

When interviewing for broadcast 'I would position a directional microphone about chest height and about 6 inches away from the person's mouth. If there is a lot of background noise I would move the microphone a lot closer, but there is then a risk of more popping and you have to turn down the recording level so the sound doesn't distort,' says Julian.

If quiet sounds need to be recorded, the best option is a capacitor microphone, as Julian explains. 'Capacitor microphones need a power supply but their response—in other words their ability to pick up much lower sound levels without so much [internal electrical equipment] noise—is much better than a dynamic microphone. You need a higher volume of sound to get a signal off the simpler types of microphone.'

4.3 Recording music

Microphone choice is also important for recording music, as Paul Paragon, a freelance sound engineer with over 20 years' experience, who took the Tonmeister Music and Sound Recording degree at the University of Surrey in the UK, explains.

'For recording live pop music, I use mainly unpowered dynamic microphones. They can take the very high sound pressure levels from loud, amplified music and pop stars singing directly into them from only inches away. You choose moving coil microphones because a lot of damping goes on [reduction in amplitude of vibrations] within the transducer itself,' says Paul, who has worked with many music artists including the Happy Mondays, Cathy Denis, and Chrissie Hynde, as well as in a range of extreme environments such as up mountains, and in conflict zones (as section 4.4 reveals).

'By contrast, when you are recording an orchestra the sound pressure levels are much lower because the microphones are positioned further away. The audience hears a wash of blended sound, so to get the same stylistic impression [on the recording] you want your microphones to be positioned either near the first row of the audience or above the conductor. Therefore you need to choose transducers that don't have much

Box 4.4. Microphones

There are several different types of microphone, but all convert sound into an electric current with a waveform representing those sounds. Most microphones used in media production contain a diaphragm which moves in response to sound. But there are two types of transducer that can be used to turn this motion into an electrical signal. One type of transducer works by electromagnetic induction, and microphones with these transducers are commonly known as dynamic microphones (see figure 4.7 for an example). The other type of transducer works via a change in capacitance.

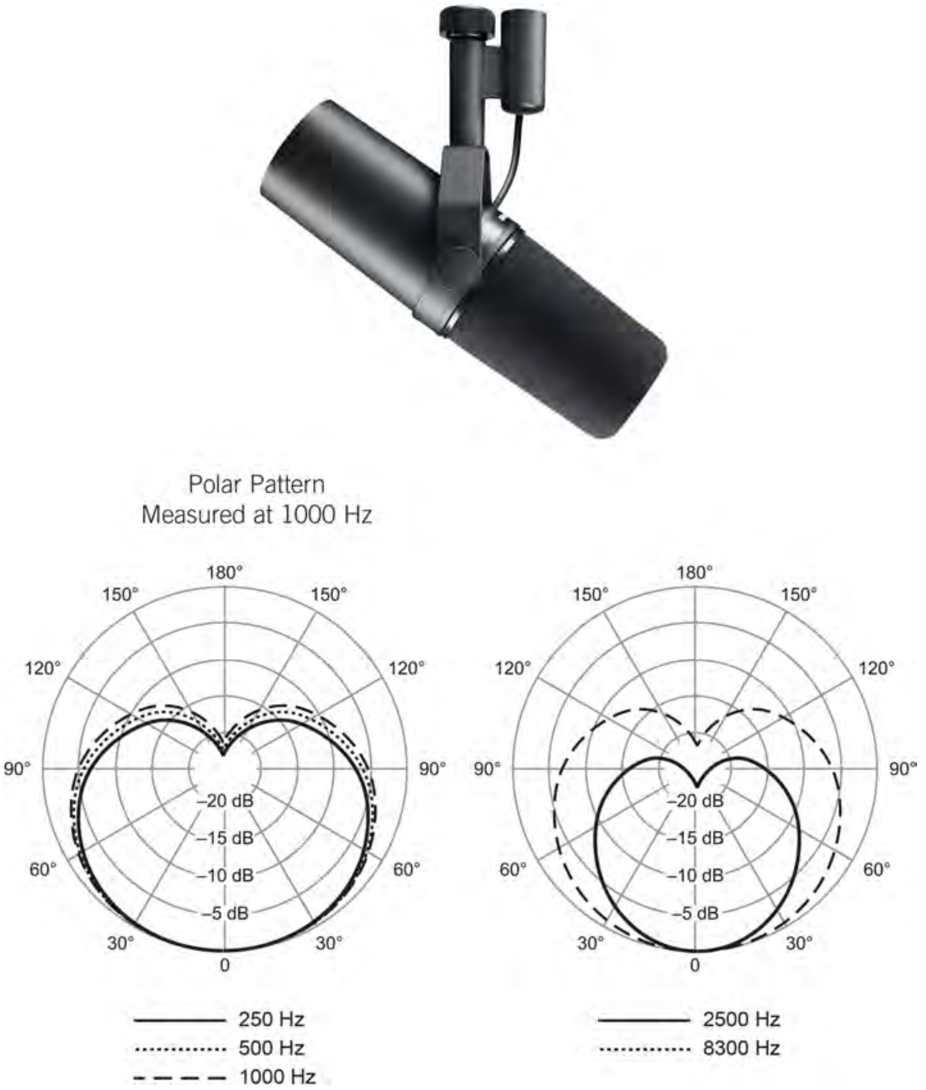

Figure 4.7. (a) The Shure SM7B studio microphone. This microphone is particularly suitable for recording speech and vocals in a studio. It is a dynamic microphone, and has a cardioid polar pattern. Polar patterns illustrate how well a microphone picks up sound coming from different directions. Cardioid microphones will mainly hear sounds coming from in front, but will also pick up some sound from the sides. They are much less sensitive to sounds coming from behind, which makes cardioid microphones ideal for situations where isolation from ambient noise is required. (b) Polar patterns for this microphone. (Images courtesy of Shure UK. Reproduced with permission.)

A moving-coil microphone is a type of dynamic microphone and is the reverse of a loudspeaker. It converts mechanical vibrations caused by sound into an alternating electric current that can be amplified then recorded or fed to headphones or a loudspeaker. Inside the microphone there is a diaphragm that is free to vibrate, which is connected to a coil of wire (see figure 4.8). If the rear of the capsule enclosing the diaphragm is closed off to the outside world, when sound waves coming from any direction reach the microphone they exert forces on the diaphragm that are proportional to the sound pressure. These forces cause the diaphragm to move in response to the sound, and as the diaphragm is connected to the coil, the coil also vibrates backwards and forwards moving in and out of the magnetic field created by a strong permanent magnet inside the microphone. An alternating voltage is induced in the coil of wire thanks to a principle known as electromagnetic induction. This voltage has the same frequency as the sound waves that induce it.

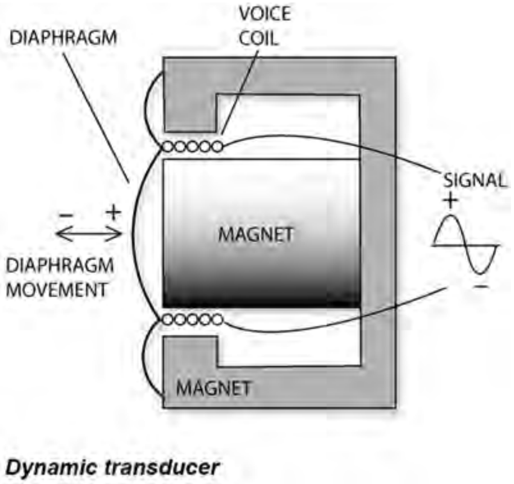

Figure 4.8. The main parts of a moving-coil microphone. This one has a closed back so is omnidirectional, which means it can pick up sounds coming from any direction. (Reproduced with permission of Bruce Bartlett.)

By contrast a capacitor microphone needs a power supply. A capacitor is an electronic circuit component which can store electric charge. It is made from a parallel pair of conducting plates separated by an insulator. The capacitance, C, of a capacitor depends on the size and shape of the plates and the distance between them, and is defined as the ratio of electric charge on either plate of the capacitor to the potential difference (in volts) between them. A capacitor microphone works by having the two plates of its capacitor charged, and as one plate can move in response to sound, the distance between the two plates varies as sound reaches the microphone. This alters the capacitance of the microphone and so causes its output voltage to change in accordance with the sound wave input.

There are three main sensitivity patterns that microphones can have. Microphones with equal sensitivity to sound from all directions are known as ‘omnidirectional’ and are closed at the rear. This means all sounds reach the front, and the voltage they create is directly proportional to the sound pressure. ‘Figure of 8’ microphones are sensitive to sound from the front and back but not the side. They are open to all directions, and give a voltage directly proportional to the difference in sound pressure between the front and back. By contrast microphones sensitive to the front and side but not the rear, which therefore have a combination of omnidirectional and figure of 8 sensitivity, have a cardioid (heart shaped) sensitivity pattern. Cardioid microphones are semi closed.

[internal electrical] noise so you need capacitor microphones,' continues Paul, adding that they are much more expensive than dynamic microphones.

'If you choose closed back capacitor microphones for which the [output] signal level is directly proportional to the sound pressure level at the point where that microphone is in space, they give very faithful sound reproduction at all frequencies in all directions,' says Paul, who has recorded several orchestras and choirs including the BBC Symphony Orchestra, the Choir of King's College, Cambridge, and the Mariinsky Opera, and at various venues around the world including the Forbidden City Concert Hall in Beijing, China, and the Royal Opera House in London.

To avoid picking up sounds from behind the conductor you can use a directional microphone, which has a combination of a closed and open back, says Paul. This is created via slots in the back wall of the capsule behind the diaphragm, and 'the microphone picks up a combination of air pressure differences across the diaphragm as well as the pressure at the front'. The microphone's response is essentially that of an omnidirectional microphone added to that of a bi-directional microphone explains Paul. This, he says, means it picks up a large amount of sound from in front, which is coming from the performance, much less at the sides, and almost nothing from the audience behind as those noises will push the diaphragm from both the front and the back at the same time with the same amplitude and frequency but in opposite directions in such a way that there is no net movement and therefore no voltage induced. The overall result is a microphone with a cardioid (heart-shaped) polar pattern that has a strong sensitivity in the front, while cancelling out sounds from the rear.

4.4 Capturing sound for TV and film in extreme environments

Despite the importance of choosing the right microphone which, says Paul, for most of his TV and film work is largely dictated by how far away the sound source is from the mike (see box 4.5), this is actually his 'final stage' when recording anything for

Box 4.5. Sound intensity

The intensity of a sound wave decreases in inverse proportion to the square of the radius of the wavefronts, which are the locations of the crests of the waves at a specific moment in time. The wavefronts spread outward and also expand as they move further away from their source (like the water waves shown in figure/video 4.2). Since the area of the wavefront is increasing, the wave energy per unit area is decreasing.

Sound intensity, I, is defined as the amount of sound energy that passes through a square metre area (at right angles to the direction the sound is coming from) in one second.

broadcast. Paul first thinks about how sound will interact with his surroundings and what he can do to improve the acoustics.

'The thing that most affects how good a sound recording will be are the acoustics of the area,' explains Paul, half of whose degree content focussed on the physics principles, electronics, and maths behind sound recording. 'Theoretically you can calculate the rates of change of vibrations, or do a Fourier analysis on the sound, but on a job you might only get a few minutes to do something to make the recording sound good.'

His approach to this can be surprisingly low tech. 'Fifty pounds spent on some blankets is worth hundreds spent on a good microphone because that will also make your interview sound better. Get the acoustic right first. Don't sit someone in a room with parallel hard walls. Instead have them facing something soft. Upholstery is your friend! All that a really expensive microphone will do is more faithfully reproduce the bad acoustic. So it's all about just turning the chair, or drawing the curtains, or putting some blankets up or lining the room with carpet,' he says, adding that he also uses bits of foam or blankets to help reduce any unwanted noises such as rain, or people walking around outside.

Paul feels that knowing the fundamental physics principles of sound has helped him have a wider and more varied career, as he can determine what he needs to successfully record sound no matter what environment he encounters. This level of physics knowledge, he says, is not something people trained to operate particular equipment via vocational courses in sound recording will have.

'Understanding the physics also empowers me by enabling me to assess how good new technologies and methods are. People will go and spend loads of money on equipment that does extra stuff that we can't actually hear. But I can put a multimeter across a new bit of gear and measure its noise and its response myself. Knowing about physics means you can't be conned. Whatever technology springs at me, the physics behind it doesn't change,' he says.

His physics knowledge also enables Paul to create or adapt equipment. 'Half of my kit is home made in my shed. Manufacturers have no idea exactly how people will use their equipment and I can make additional equipment so one piece of kit that doesn't normally connect with another will work. I also build my own power supplies.'

While the equipment Paul uses in each scenario remains the same, he does need to take extra care of it in certain environments. 'Gear behaves differently in different atmospheric conditions,' says Paul, who has recorded up mountains and volcanoes (see figure 4.9). 'Hard drives won't work at altitude for example because the read heads need air to fly above the discs, but this problem has been solved as now we record on solid state drives.'

Extremes of temperature can however cause issues. 'Don't go into the freezing cold unless you've got rubber cables. PVC [insulation around cables] goes stiff, and when it goes stiff it transmits noise down the cable. Noise on the cable gets picked up by the microphone and you've got a poor recording. In hot environments, direct sunlight can ruin displays,' explains Paul, adding that whatever the temperature using a good wind shield is very important for stopping the sounds of wind buffeting from reaching the microphone.

Figure 4.9. Sound engineer Paul Paragon recording over the rim of an active volcano in 2016. A fluffy wind shield protects his microphone from unwanted wind buffeting. (© Clive Oppenheimer. Reproduced with permission.)

'You need to have still air around your microphone, so you can use a wind shield that is a cage with fur over it [as in figure 4.9] rather than a little foam one which is still going to transmit seismically the wind vibrations. If you've got a big basket over the microphone it has a volume of still air next to it, and the sounds [that you want] have got a high enough frequency to pass through the wind shield unlike the [much lower frequency] seismic vibrations of the wind buffeting,' says Paul, whose recordings for science documentaries have involved being chased by hippos and elephants, living with remote tribes, and donning a silver heat suit and gas mask to enable recording from the rim of an active volcano.

Paul says his physics knowledge has also helped protect him when working in hostile environments, including conflict zones. 'If you look at the world through the lens of physics, it puts you in a good position for dealing with new situations and environments. When I've worked in areas with land mines or under small arms fire, my knowledge of physics helps me be continually aware of what kind of features of the local landscape or environment can protect me. If you are covering conflict, you need to learn about the damage that can be done by different types of ordnance, and what best protections there are in the environment for shielding yourself from fire should you need to duck for cover.'

4.5 A recording method of the future?

We have magnetic recording, and more recently solid state recording, to thank for not only preserving broadcast content and the music of our favourite acts, but also for enabling streaming and downloading of audio over the Internet. As we become more dependent on cloud-based storage for the digital content we save, data centres are increasing in size and using ever greater amounts of power for writing and storing data magnetically. According to Alexey Kimel, a physicist at Radboud

University in The Netherlands who is researching a new method of magneto-optical recording, 'servers and data centers consumed 61 billion kWh (kilowatt hours) in 2006. This was 1.5% of total U.S. electricity consumption that year, amounting to \$4.5 billion in electricity costs—equivalent to 5.8 million average US households.' Alexey and his colleagues are developing a new method for storing data magnetically that would use much less energy, and record data 100 times faster than current technologies.

In a magnetic material, the atoms are arranged within tiny areas known as domains such that each domain behaves like a very small magnet. These domains can be magnetised in two directions, either 'up' or 'down', and in magnetic storage systems a domain is magnetised one way to represent a 0 and in the other direction to represent a 1. 'We are studying how we can control magnetic media with the help of short laser pulses. If you shine a laser pointer on a magnet, it will do nothing to the magnet. But if you use a laser that generates very short laser pulses in which the light power is concentrated in less than a hundred femtoseconds—1 fs is 10^{-15} s, so 100 fs is 10^{-13} s—and move that laser beam across a magnet it will reverse the magnetisation,' says Alexey. This ability to reverse magnetisation would allow digital data to be recorded using a femtosecond laser as it could change the magnetisation within each individual domain of a suitable magnetic recording medium. (Figure 4.10 illustrates the basics of the process.)

On this sort of timescale, the normal laws of magnetism don't apply because they only hold for situations in 'thermal equilibrium' in which no heat is being exchanged between different parts within a system, or between the system and its surroundings.

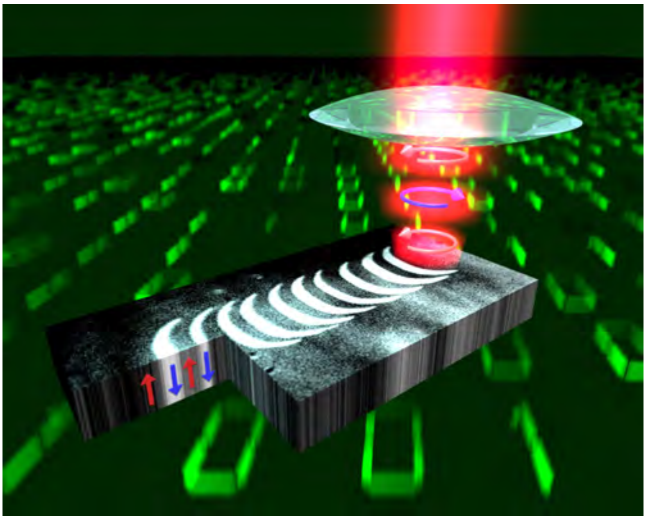

Figure 4.10. Femtosecond laser pulses could be used to create a new type of optical magnetic recording system. In this illustration, the white areas represent an 'up' magnetic domain, while the black areas represent a 'down' domain. (Courtesy of Alexey Kimel. From C D Stanciu, A Tsukamoto, A V Kimel, F Hansteen, A Kirilyuk, A Itoh and Th Rasing, 'All-optical magnetic recording with circularly polarized light', *Phys. Rev. Lett.* 99, 047601 (2007). Reproduced with permission.)

As Alexey explains, they are creating a system in a state away from thermal equilibrium that hasn't ever been studied before. 'We didn't even have a language to describe this state because such a thing as the temperature which is very often used to describe magnetic phenomena is simply not defined for a non-equilibrium state [like this]. You can define temperature only when the system is in equilibrium.'

Before a system reaches equilibrium 'something weird can happen and what we see because these laser pulses are so short is that they can reverse the magnetisation of a magnet,' continues Alexey. This reversal of magnetisation happens 100 times faster than in normal magnetic recording devices. 'If you look at how much energy is left in the [magnetic recording] medium by this reversal, it appears that it is at least 1000 times less than in comparable devices that are using magnetic recording these days. So we can reduce the amount of heat dissipated in the recording medium,' explains Alexey, adding that this would help data centres as they currently use a lot of energy for cooling.

While solid state drives are taking over from magnetic storage in some applications, he explains that this has a short lifetime compared with magnetic storage media. 'Really important information should be stored magnetically where the information can survive without applying voltage to the storage device. Solid state drives require a regular application of voltage to them so they are not reliable. They are cheaper and lighter, but important data still requires magnetic recording so this is used in cloud storage.'

'So far [what we are seeing] is poorly understood, but it is technologically very appealing and that's why we are studying these phenomena. What we're trying to understand now is if you take a magnet and shine a short laser pulse at it how does it respond? It's not just that it reverses the magnetisation. So we want to know what phenomena are taking place in this ultra-fast magnetism which is on a timescale much faster than electronics works these days,' continues Alexey.

While much of Alexey's research uses relatively large laser beams so his team can measure the effects faster, a special study in collaboration with Stanford University in the United States revealed that with the help of special antennas light can record domains smaller than the wavelength of light. To be able to visualize such domains, a free-electron laser in the x-ray spectral range (which has a smaller wavelength than light) was used. It was shown that bits as small as 40 nm across could be written. This bit size, says Alexey, is comparable to the 10 to 20 nm bit size for data postulated by researchers working on improving conventional recording techniques.

As this work is currently fundamental research, Alexey warns that it could take many years to be turned into a commercially available technology. Also, due to the large size of the lasers used, and their high cost (around €100 000) he thinks the first applications of this type of data storage system would be in data centres, and in other unique environments such as space. In principle though, this new magnetic recording technology could eventually filter down into wider use.

'I don't see a fundamental problem with scaling femtosecond lasers down in size and making them cheaper and there is research in this direction. When new applications come from fundamental research like this the resulting technology would be an expensive technology though so it is more likely to be used for specialist applications,' says Alexey. As the technology would also be capable of sensitive detection of magnetic fields, he feels it could also find a use in healthcare for monitoring heart function from a few centimetres away from the body by detecting the magnetic fields produced by the heart's electrical activity.

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Paul Paragon's website
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Optomagnetism research at Radbound University in the Netherlands

IOP Concise Physics

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Volume 1: Physics in the arts, architecture and design
Sharon Ann Holgate

Chapter 5

Music to your ears—the physics behind music

5.1 Introduction

Physics may be the last thing on our mind when we listen to our favourite music, but without physics we wouldn't hear anything at all. Instrument makers harness the acoustic properties of the materials they use in order to create a pleasant sound, while electromagnetic effects enable electric string instruments such as electric guitars to be heard.

I first became interested in the physics of music in the 1990s when I attended a public lecture on the physics of violins by physicist Peter Townsend, my then Doctoral supervisor, now an Emeritus Professor at the University of Sussex in the UK. Peter is a classically trained violin player who has given university courses on the physics of music. In this chapter he explains the physics that allows violins to produce sound.

We will also see how vibrations set up in some other instruments create their signature sounds. Firstly, how a drum generates sound is revealed by my friend Larry Crockett, a professional drummer for over 30 years who has worked with many music artists including Eric Bibb, Elton John, and Motown legends Martha Reeves and The Vandellas. Larry studied music at University, and teaches master classes for students all around the world when he is not gigging.

Finally this chapter looks at how guitars create sound, with the help of Mike Pycraft-Hughes from the Department of Mechanical Engineering Sciences at the University of Surrey. I first interviewed Mike for a short BBC World Service radio feature on the construction of electric guitars. In this chapter he describes how acoustic and electric guitars produce their respective sounds.

5.2 The physics of violins

The musical notes we hear from acoustic instruments are sound waves that have been induced by mechanical waves in the instrument. While sound waves travel through the air to our ears (see box 4.1), the mechanical vibrations set up by playing a musical instrument are stationary waves (see box 5.1).

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Box 5.1. Stationary waves

A stationary wave can be set up in a stretched cord that is fixed at one end. First a vibration is created at the free end by moving the cord to and fro. This creates a travelling wave (also known as a progressive wave) that travels along the cord and is reflected from the fixed end. The reflected wave travels back along the cord heading for the moving end, where it is reflected again and is subsequently reflected off either end of the cord in turn.

If the free end of this stretched cord is kept vibrating while this original wave reflects to and fro, there will be progressive waves with the same frequency and amplitude (see box 4.2) travelling at the same speed in opposite directions along the cord. These waves then interact to form a stationary (also known as a standing) wave which does not move.

The nodes of a stationary wave are the points where there is no movement of the solid, liquid, or gas making up the wave so the displacement is zero. By contrast the antinodes are the points of maximum displacement where the amplitude of the stationary wave is at its maximum.

Musical instruments produce sound thanks to the setting up of stationary waves like this. For example, figure 5.1 shows the nodes and antinodes of a vibration on a string, such as in a violin, guitar, cello or piano, while figure 5.2 shows a vibration in an open pipe which is the type of vibration set up in instruments that behave essentially like cylindrical tubes open at each end such as the flute or piccolo. By contrast the structure of some instruments including the clarinet leads to vibrations like those of a pipe closed at one end, as shown in figure 5.3.

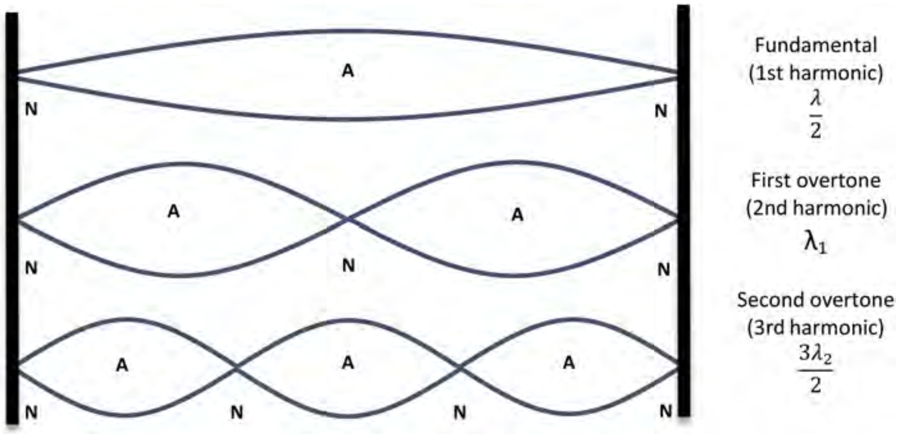

Figure 5.1. Vibrations on a string. Each vibration shown is a stationary wave. At each node the displacement is zero, while the antinodes are the points with the greatest amplitude.

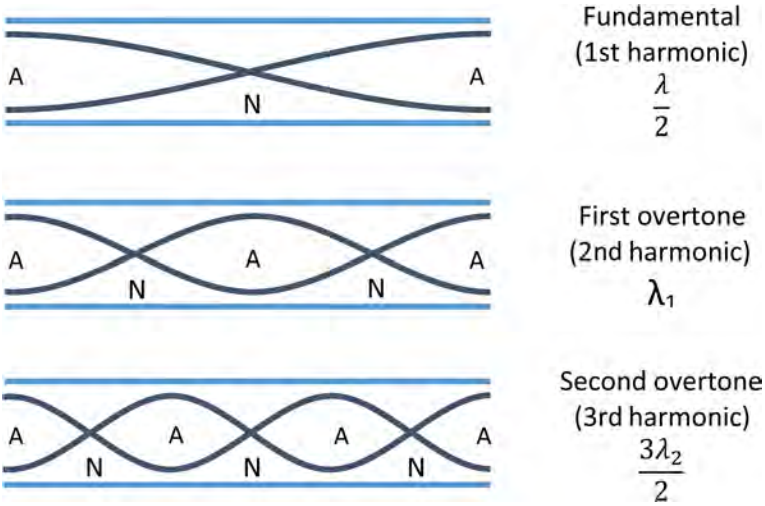

Figure 5.2. Vibrations in an open pipe, in which the points marked N are the nodes, and A indicates the antinodes.

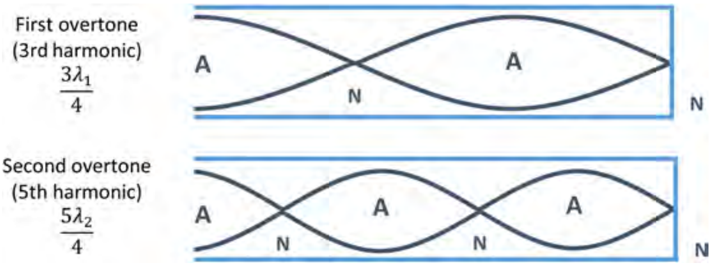

Figure 5.3. Vibrations in a pipe closed at one end, showing the nodes, N, and antinodes, A.

Perhaps surprisingly, a vibrating violin string (see figure 5.1) produces very little sound. But when a bow is drawn across a string, the resulting vibration of the string is transferred to the main wooden body of the violin. The consequent vibration of the front and back plates of the body then amplifies the sound in a similar way to a speaker, producing the characteristic sound of the violin. (See box 4.3 for an explanation of how headphones and loudspeakers work.) In a speaker, a moving diaphragm sets up vibrations in adjacent air molecules. In a violin, the vibrations of its body cause the air enclosed in it to vibrate.

Both the violin body and the enclosed air have several natural frequencies at which they can vibrate, so can resonate—and thereby produce a loud sound—if the bridge (figure 5.4 shows the main features of an acoustic violin) drives them with a frequency the same as one of these natural frequencies. (See box 5.2 for more on resonance.)

Box 5.2. Resonance

When an elastic object is subjected to a force that changes its shape suddenly, such as when a string is plucked or a drum head is hit, the object will vibrate at a frequency known as its natural frequency. The value of an object's natural frequency is dependent on the physical properties of the object.

If an alternating force (known as a driving force) with a frequency the same as that of the natural frequency is applied to an object large amplitude vibrations result. This effect is known as resonance. The resulting resonant frequency is generally very close to, but not identical to, the value of the natural frequency.

It is not just mechanical systems that can show resonance. It can also be set up in electrical circuits and molecules.

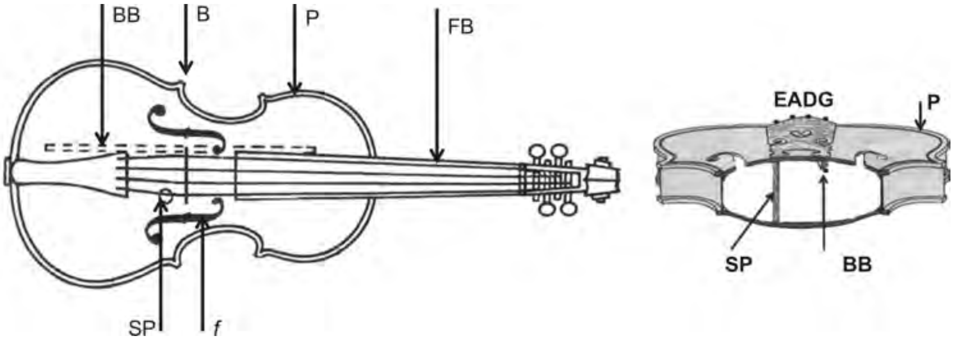

Figure 5.4. The main features of an acoustic violin. In the left-hand view, FB is the fingerboard, P is the purfling inlay (which stops the violin body from cracking if you accidentally hit the edge), B is the bridge, BB is the bass bar, SP is the sound post, and f is the sound hole. In the right-hand view, the E, A, D and G strings are indicated, as are the sound post, bass bar and purfling inlay. (Figure 3 from The role of physics in shaping music by Peter Townsend, *Contemporary Physics*, 2014, reprinted by permission of Taylor & Francis. Ltd http://www.tandfonline.com.)

The piece of wood between the violin's f-holes, which supports the strings, is known as the bridge. The bridge transfers the vibrations of the strings to the violin's main body. Each of the four strings has its tension adjusted by tuning pegs at the end of the bridge (see figure 5.4) and each string is tightened by a different amount so that it produces a different pitch. (See box 5.3 for more on pitch.) The greater the amount of tension in a string, the higher the pitch it produces.

The notes G, D, A and E are produced by adjusting the string tensions to respectively have fundamental frequencies of approximately 200, 300, 440 and 660 Hz. 'Mathematically the actual notes you get are a mixture of the fundamental and its harmonics [see box 5.3]. So for 200 Hz you get 200, 400, 600 and 800 Hz,' says physicist and keen amateur violin player for the last 75 years Peter Townsend, adding that the tone produced by the violin is similar to that of a flute because they have the same harmonics. (See figures 5.1 and 5.2.)

Box 5.3. Musical notes

The pitch of a note describes how high or low it sounds. It is mainly dependent on the frequency of the vibration of the air that makes up the sound wave that reaches our ears, which is itself the same frequency as that of the sound source. Higher frequencies correspond to higher pitched notes, and vice versa. For example, the vibrating A string of a violin (which is the A above middle C) has 440 vibrations per second, in other words its pitch is 440 Hz, while the violin's E string (which is higher on the musical scale) vibrates at 660 Hz.

If the same note is played in different musical instruments it will not sound exactly the same. This is because musical notes do not consist of just one frequency. Instead they are made up from a 'fundamental' note which has the lowest frequency, and other, generally fainter, notes called 'overtones'. If the frequencies of the overtones are multiples of the fundamental frequency they are known as harmonics. The number of overtones in a given note, and their respective intensities, differs depending on the instrument and changes the sound of the note. (See figure 5.5.)

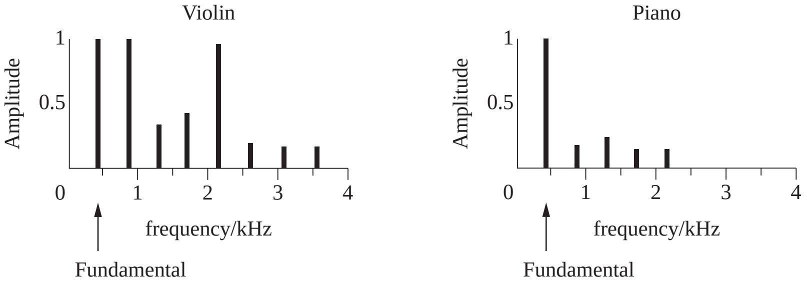

Figure 5.5. The harmonics produced by a violin compared with those produced by a piano for the musical note A above middle C, which is at 440 Hz.

The frequency of the fundamental part of a note is the frequency by which that note is described. This frequency is labelled f, and can be referred to as the 'first harmonic'. The overtone with a frequency of 2f is called the second harmonic, while the overtone with frequency 3f is known as the third harmonic, and so on. Not all harmonics produced are audible as some have frequencies beyond the range of human hearing, but several harmonics can be heard. For instance, the second through to the sixth harmonics of the C note on a piano are audible.

These harmonics have been produced because like the strings in all stringed instruments the string that creates the piano note can vibrate in several different ways simultaneously. Three of the vibrational modes (in other words ways of vibrating) possible for a string are shown in figure 5.1. When the string vibrates in two sections the second harmonic is heard, while the third harmonic is produced when the string vibrates in three sections.

Similarly the air in pipes can vibrate in several ways at the same time, producing overtones. However whereas in an open pipe (see figure 5.2), like a string, all harmonics can be produced, in a pipe closed at one end (see figure 5.3) the air vibrates in such a way that only the odd-numbered harmonics can be produced. The same note played on an instrument that behaves like a closed pipe and on an instrument that behaves like an open pipe will therefore sound different.

'There are just over two octaves on each violin string, and you use your fingers to shorten the length of the string [by pressing the string against the fingerboard] to get higher notes. So effectively the string length is where you put your finger down,' says Peter, explaining that as violin players can move across the strings as well this gives violins a range equivalent to the G below middle C on a piano up to the top end of the piano keyboard.

'When strings get hot because they have been played hard they stretch, so to stop the violin from going out of tune you use the tuning pegs to alter the string tension,' continues Peter. Binding strings with a metal such as silver gives them more mass and 'can make strings insensitive to temperature', he says. Strings with more mass also give a louder sound because they move more air when they vibrate.

The action of the bow (see figure 5.6) on a string produces a sawtooth pattern of movement in the string (see figure 5.7). 'The bow is made from horse hair covered in a sticky resin, and the pulling action of the bow on the string is the linear bit of the sawtooth wave. Fly-back occurs when the frictional force from the bowing action cannot hold the string any more, and so it whips back to its starting position,' explains Peter.

The bow sets up a transverse vibration in the string which in turn creates a resonance in the bridge as well as vibrations in the body. 'A good violin body will resonate at the fundamental and several of the higher harmonics for each of the notes,' says Peter. The f-holes allow the consequent vibrations of the air inside the violin's body to be transmitted out as a longitudinal sound wave. The frequency of this sound wave is the same as that of the transverse vibration on the string, so the note played on the string is what we hear.

A 'sound post' that is held under tension between the back and front plates of the main body at right angles (see figure 5.4) transfers the vibrations set up (via the bridge) in the top plate of the violin's body to the bottom plate. The front and the

Figure 5.6. A violin bow. The long piece of wood that the bow is carved from is known as the stick. The part of the bow that comes into contact with the strings is made from horse hair. A piece of leather, normally wrapped with fine silver wire, known as the grip goes round the stick where the bow is held. (Shutterstock image ID: 98221169. © pixomar/Shutterstock.com.)

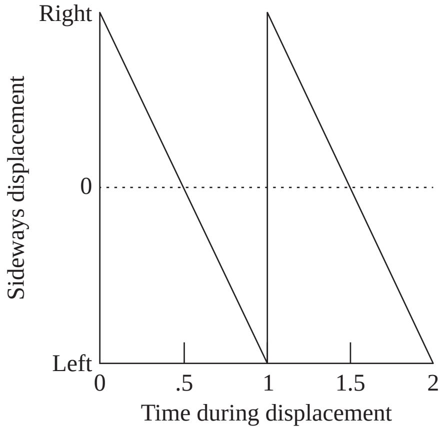

Figure 5.7. The frictional forces created by a horse hair bow covered in resin being drawn across a violin string cause the string to move in a sawtooth pattern, as illustrated in this diagram. (From The role of physics in shaping music by Peter Townsend, *Contemporary Physics*, 2014, reprinted by permission of Taylor & Francis Ltd http://www.tandfonline.com.)

back of a violin in fact behave like drum heads and vibrate differently, says Peter, adding that without a sound post a violin would radiate less sound.

Several changes have been made to the violin's construction over the centuries, and although many concert violinists play old instruments, they are not quite what they seem. 'Almost all of the old [18th Century] violins now in use have been modified,' says Peter, explaining that they have a longer finger board and more curved bridge than they did originally, which enables the higher notes and more complex chords from more modern music to be played. 'They [also] use strings which are not just catgut but have a lot more mass to them because that gives you more volume. Because you've got more mass you need more tension to get the same frequency. More tension there [in the strings] puts higher pressure on the body and a lot of the early instruments just collapsed [when the strings were replaced], so they need to have a different bass bar [which strengthens the top of the violin and also improves its sound (see figure 5.4)] to be more supportive,' continues Peter.

The air in a violin body vibrates at a frequency near to the resonance of the D string, so all violins will produce a good sound near the D. But to get good tone you need the plates to vibrate in specific ways, which will be influenced by the shaping of the wood, how it varies with thickness, and the grain in the wood, explains Peter.

'Stradivarius would tap the wood [before building the violin] and hear the resonances. He typically built to get a resonance near the G and a resonance near the A string [as well as having the resonance near the D string]. So that gave you three good resonances, and big power on D, G and A,' says Peter, adding that 'you don't want much power on E otherwise it sounds scratchy. In the 19th Century they used powder to see the vibration patterns in the wood,' he continues, 'and on modern violins they use holographic imaging to see the patterns.'

5.3 The physics of drumming

As professional drummer Larry Crockett explains, the materials that the basic components of a drum are made from influence the sound it produces.

‘The shell is very important for the overall sound of the drum. Shells are often made of maple or hickory, but can be made of hard plastic or exotic woods. Each different type of shell affects the sound. For example, the plastic shells reflect the sound very rapidly because opposed to the different wood shells the plastic shells don’t absorb much sound. They mainly reflect it. Besides the shells, you have the rims which are for the most part all metal chrome. This allows the drummer to tune the drum heads [via metal tuning screws on the rim that alter the drum head tension] according to their taste and preference,’ he says.

‘For instance jazz drummers normally tune their drum heads rather tight so it projects clearly all of the minute rhythms they play. Rock or funk drummers often prefer their heads not so tight to give a ‘fatter’ sound—a sound with a longer, warm tone. Because they usually don’t play very intricate subtle rhythms on their drums they are more concerned with having a big sound that covers more space and time,’ continues Larry, who hails from New Jersey in the United States, but now lives in Paris, France.

It is the advent of plastic drum heads that has made this process possible. ‘There are different types of drum heads such as plastic with different textures on the playing side. The original name for drum heads, drum skins, was very accurate as they used to be made out of cow hide. They were very difficult to manage as cold weather conditions could cause them to tear easily or not sound good, and on very hot days they would also change their sound. Now with the many different plastic drum heads along with being able to tune drums, life is much easier for drummers,’ explains Larry, whose studies during his four year Bachelor of Music degree from Rutgers, The State University of New Jersey in the US included science and maths alongside courses on the history of music, and on creating musical arrangements, as well as classes to improve his piano and drum playing techniques.

Innovations in technologies and materials are, he says, continually coming through into drumming. ‘For example, the drums I play—DW Drums—have developed an original innovative patent. They have wooden shells that resonate at a specific note like a guitar string. So the drum is already melodic before adding the [drum] head or tuning. So now a drummer can order a drum set with his or her preference of notes for each drum, now resembling a piano or other melodic instrument. If the shell’s original vibration is, for example, the note of C, then when you tune the drum head it arrives at that note of C quite naturally. You don’t have to fight to find it. The sound is there already so there’s a lot less tuning required. With drums that don’t have a specific vibrational frequency in the drum itself, sometimes it can be difficult to find a good note to tune the drum to. But when you have this system it is easy to tap into the vibration of the shell and find a similar, or the same note that is the natural vibrational frequency of the shell,’ explains Larry. (See box 5.2 for more on natural frequencies.)

No matter what type of drum you choose, the sound it produces will differ depending on how hard, and where on the surface, you hit the drum. ‘In general, the centre of the drum is the sweet spot. The drum gives its fullest, purest sound there, which has [several] overtones as there is space for the sound to vibrate. When you go outside that little two or three inch diameter the overtones are not as pure, and don’t give as pretty a sound. If you look at any drum you will most often see the worn out circle in the centre of the drum head, indicating that this is where the drummer hits the drum most,’ says Larry. (Figure 5.8 shows Larry about to strike the centre of a drum head during a rehearsal for a 2016 gig in Germany.)

‘When you tap the drum head near the rim, you’re hitting closer to the frame than to the centre of the drum where you have all the resonance of the drum head. [See box 5.2.] So this gives a “thin” sound—which jazz drummers use as an effect to play certain drum rolls—with fewer overtones and less sustain as there is less space for the vibration,’ continues Larry, adding that you can hear this type of difference in sound by speaking or singing a note with your mouth wide open, then speaking or singing again with your mouth almost closed. ‘When your mouth is open you get more resonance and a purer sound than when your mouth is practically closed and there is less physical room for the vibrations,’ he explains. (See box 5.4 for more about vibrations on a drum head.)

While rock drummers might hit the drum so hard that they damage the drum head and have to replace it with a new one for every performance, ‘if you’re not banging the drum very hard it requires just a little tuning each night because after

Figure 5.8. Larry Crockett preparing for a gig with the Eric Bibb & Jean Jacques Milteau group at the Rheingau Musik Festival in Germany in 2016. (Photographer: Ansgar Klostermann. Reproduced with permission.)

Box 5.4. Normal modes of vibration on a drum head

If physicists want to analyse the vibrations on a drum head, they think of it as a circular membrane with the same tension throughout that is stretched over a circular ring with a radius, r. Unlike a violin string or the air in an organ pipe in which the vibrations can only travel in one direction, a stretched membrane vibrates in two directions—from side to side, and up and down. Figure 5.9 shows some of the different ways a drum head can vibrate, known as the ‘modes of vibration’. Whatever mode of vibration the membrane is in, the rim will always be a node. (See box 5.1 for more on nodes.) As with a violin string, as the tension in the membrane is increased its vibrational frequency increases, and so the pitch of the note produced goes up.

The fundamental frequency (see box 5.3) of an ideal circular membrane is given by the following equation

$$f_1 = 0.766\frac{\sqrt{T/\sigma}}{D} \tag{5.1}$$

where f_1 is the fundamental frequency, T is the tension of the membrane in units of Newtons per metre (N m^{-1}), σ is the density in kilograms per square metre (kg m^{-2}) and D is the diameter of the membrane in metres (m).

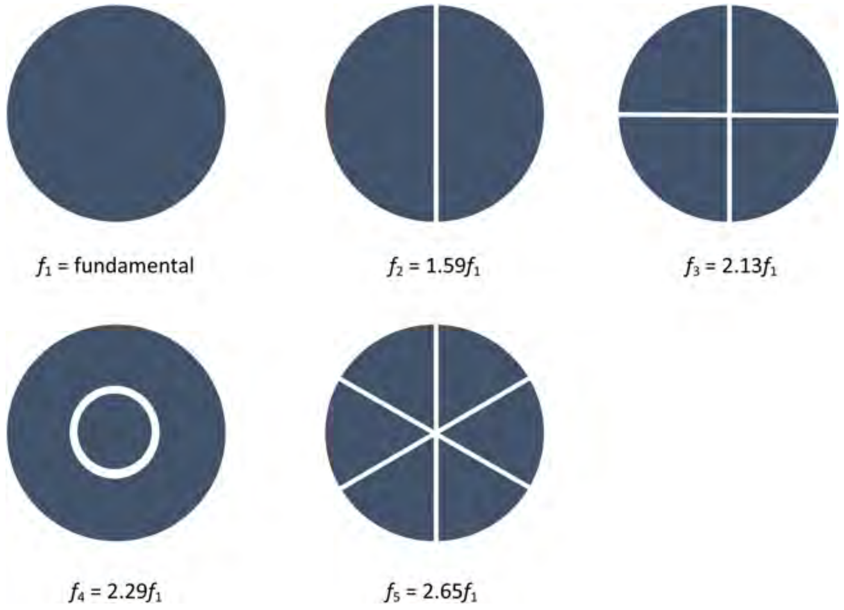

Figure 5.9. Some of the vibrational modes for a drumhead, where f_1 is the fundamental frequency for which the entire drumhead vibrates up and down with the greatest amplitude in the centre, and no movement at the rim. For the overtones f_2 through f_5, the white lines show the nodes, N, where displacement is zero. For all the overtones, adjacent sections of the drumhead move in opposite directions to each other when they vibrate.

Unlike those produced by strings and pipes, the overtones created by a vibrating membrane are not integer (whole number) multiples of the fundamental frequency. These sorts of overtones are known as non-harmonic overtones.

Figure 5.10. A common drum set-up for Larry Crockett, with annotations showing the different types of drum and drumsticks. Larry is holding wood sticks made from American Hickory. (Photo taken while Larry was preparing for a gig with the Eric Bibb & Jean Jacques Milteau group at the Rheingau Musik Festival in Germany in 2016. Photographer: Ansgar Klostermann. Reproduced with permission.)

you've played they do tend to drop out of tune a bit,' says Larry. This has been made easier, he says, by the development of small circular plastic washers that sit under the tuning screws and stop the drum head from de-tuning. 'The plastic washers prevent the screws from loosening, which is how the drum head loses its tuning,' explains Larry, who tunes each of the drums in his kit (by ear) in harmony with one another rather than tuning each to a specific note.

'The basic drum set consists of a snare drum, bass drum (the biggest size drum of the set), tom toms of different sizes and number, cymbals, and all of the hardware or stands to support it all. Sometimes I don't even use tom toms because it's not needed in the music. But I will always have a snare or bass drum, if not both of them,' continues Larry. (See figure 5.10 for an annotated photograph of one of Larry's set ups.) Each of the different drums in the kit produces a different type of sound.

'The most important drums are the bass drum and the snare drum because although drummers use many different set ups (meaning how many drums they use and the arrangements), they all use a snare drum and bass drum. The snare drum has been around much longer. These were the drums being played in the American Civil War. A similar snare still exists in parades and the marching bands at sporting events. The bass drum is more modern, and comes in a variety of sizes, and besides drum kits they are also used in parades or marching bands,' says Larry, who tunes his tom toms differently depending on what type of music he is due to be playing.

'You need the drums to match the music so if I'm playing jazz for instance, it is music that I would want to interpret and I'd also want to have an inter-play with the other musicians. There's a lot of call and respond, so one person plays something and then you might want to put your two cents in there to respond, or to support what they play. So you need the sound to be quick. A long, drawn-out, heavy sound would cover up what the other musicians were playing. So with jazz I'd tune it to a higher pitch. The tighter you tune the drum head, the higher the sound pitch goes, and that gives you the quicker response with less sustain on the note. If it is Motown or R&B music, you want the sound to be more blended in. You don't jump in [as with jazz], the musical relationship is more supportive. You want the sound to be non-disturbing and warm, round and full so you tune the drums lower than a normal jazz drum,' explains Larry, adding that while he uses these rules for tom-toms, the snare drum needs treating differently. (See box 5.3 for more on pitch.)

'The snare drum is usually tuned relatively high and tight as this gives direction and intensity to the music so that doesn't change a lot as far as the variables of tuning are concerned. It can be a little tighter or looser, but generally it must not have a lot of sustain because the drummers are really hitting it pretty hard,' says Larry.

The vibrations produced in a drum head can last for one second to several. 'It depends on the tuning and/or the amplification of the drum. A drum can sound totally different when being amplified with a microphone. The sound can last for a very long or very short time depending on how the sound engineer wants it to sound. It can affect ones playing a lot negatively or positively,' Larry says. (See sections 4.2 and 4.3 of chapter 4 for more on microphones.)

'Imagine if you were to speak and every word you spoke lasted five seconds. It would force you to speak slower in order to be heard. But what if you didn't have time and needed to say something quickly? It would be a mess. Or if you had lots of time to say what you needed but the response from your friends was very slow in coming. You might feel the uncomfortable void and begin saying too much to fill in the gap. Similarly imagine a drummer playing a ballad which is very slow but his or her sound vibrated very short. It wouldn't fill the necessary space, causing the drummer to either speed up or play more than needed to fill the space. Either way it forces the drummer to play unnatural and uncomfortably,' explains Larry.

The type of drumsticks used by a drummer will also alter the sound. 'The most popularly used wood sticks are made out of maple or hickory. There are also carbon fibre sticks that don't break, but sound rather hard. Rock drummers such as Lars from Metallica, or Tommy Lee from Mötley Crüe, use these types. I prefer the maple wood sticks because they give a warmer sound, and they feel more natural in the hands. They all come in different sizes, lengths, weights and with plastic tips if you like. All of this affects the way a drummer plays and the sound that comes from the drum. For example, a big heavy wooden or carbon fibre stick will likely be used to pound hard on a drum to get the biggest attack and sound. Whereas a lighter stick is used to play faster and with more precision,' Larry explains, adding that there is an ever increasing range of drumsticks becoming available, such as drumsticks with shakers on one end 'so you get two different effects with one stroke'.

When deciding what type of drumstick to use, he feels this 'should always depend on two things. Firstly, on one's hand size and strength. If you are comfortable with the feel of the stick then that's a great start. Secondly, it depends on the music you are going to play. If it's jazz, you might be better off with a lighter stick. If you are hitting very hard, then a medium to heavy stick would fit best. Besides if you hit very hard, you might break the lighter sticks easily. I personally use a medium size wood stick (see figure 5.10) because I need precision and power in most of my musical situations.'

Larry also uses a range of drumsticks with different ends (shown in figure 5.10) for particular effects, as he explains. 'A splashstick gives a different sound than a normal stick. Because it has many little strands of sticks, it gives a more tribal, less precise attack sound. An acoustic stick is similar to the splashstick but is made of plastic. This gives it a brighter, but less aggressive sound than the attack of a normal stick. Mallets are more popular in classical music used on the tympani drums. They give a warm, soft, round sound and are good for making long sustainable clouds of sound, whereas brushes are used typically in jazz music. They have a very delicate and light touch and are predominantly used to play ballads. [As a demonstration] if you rub your hands together you will get a sound similar but not as refined as brushes.'

5.4 How guitars produce sound

Despite looking quite similar, acoustic and electric guitars create sound in very different ways as Mike Pycraft-Hughes, a professor in the Department of Mechanical Engineering Sciences at the University of Surrey in the UK who has studied the physics of electric guitars, explains.

'An acoustic guitar is designed to have the whole system of producing notes and projecting them out to the audience built into a single frame. So you've got strings that you pick and a neck that allows you to select which note you want. That then connects onto a large board [the soundboard] and as a string vibrates it moves that board up and down, which moves air and effectively acts like a loudspeaker and allows the guitar to project,' explains Mike. (Box 4.3 explains how speakers work.)

Acoustic guitars work in a similar way to violins, with the strings and consequently the body vibrating, which in turn sets up vibrations in air. 'A guitar is basically a box. You can get guitars made out of old cigar boxes and oil tins. The main thing is that as the strings—which are attached to the top of the guitar—move up and down, they move the top up and down. Most guitars have a hole, which is known as the sound hole (see figure 5.11), and this allows two things to happen. It enables part of the top to move more freely because it is not constrained all around like a drum—one edge is effectively free to move because that's where the hole is,'

Figure 5.11. Detail view of the sound hole and strings of an acoustic guitar. (© Marcus Miranda/Shutterstock.)

Box 5.5. Pick-ups

Pick-ups rely on the principles of electromagnetism. A simple electric guitar pick-up contains a permanent magnet with a coil of wire wrapped around it. When the vibrating metal guitar strings move in and out of the magnetic field created by this magnet, an electric current is induced in the coil of wire. The induced current has the same frequency as the guitar string vibrations, so the current flowing from the pick-up creates the sound we hear once it has been fed through an amplifier.

There are many different designs of pick-up, which all influence the end sound we hear. For example, some pick-ups contain two coils wound in opposite directions to eliminate hum from mains power and electric lights, and the magnets in some pick-ups are made from a ceramic while others contain Alnico (an alloy of aluminium, nickel and cobalt) magnets.

says Mike, adding that the movement of the top of the guitar produces its own sound which it radiates out. ‘Secondly because you’ve got the sound hole, the air which is inside the hole gets squeezed out as the soundboard [first] moves up and then squeezes down. So that produces a second source of sound. Both of these things can set the tone of the guitar.’

‘The tone will alter depending on the size of the soundboard, because the larger it is the lower its resonant frequency will be [see box 5.2 for more on resonance],’

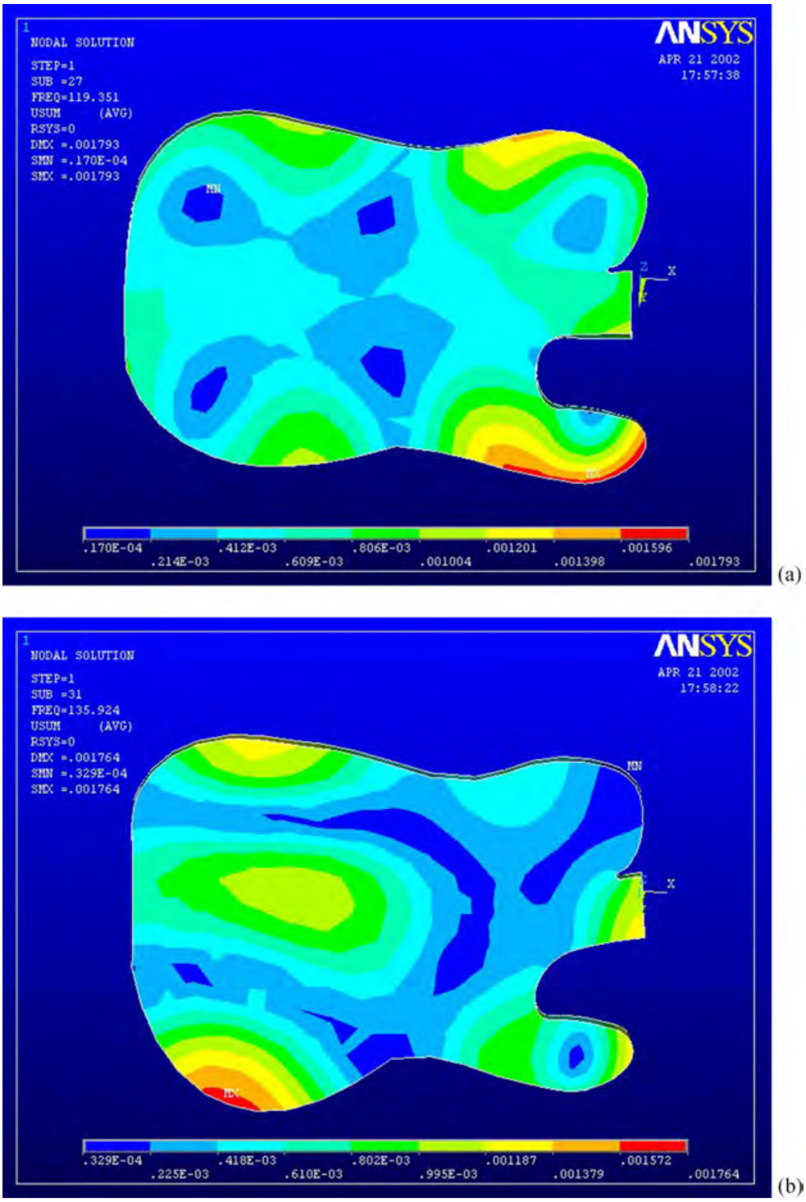

Figure 5.12. Computer modelling of a Fender Telecaster guitar body vibrating at different frequencies (a) 119Hz; (b) 135Hz; (c) 255Hz; (d) 744Hz. The dimensions of each real life guitar studied were measured to enable an accurate CAD representation to be made. This was then imported into FEA (finite element analysis) software, which generated the images shown here. (© Michael-Angelos Psiakis. Reproduced with permission.)

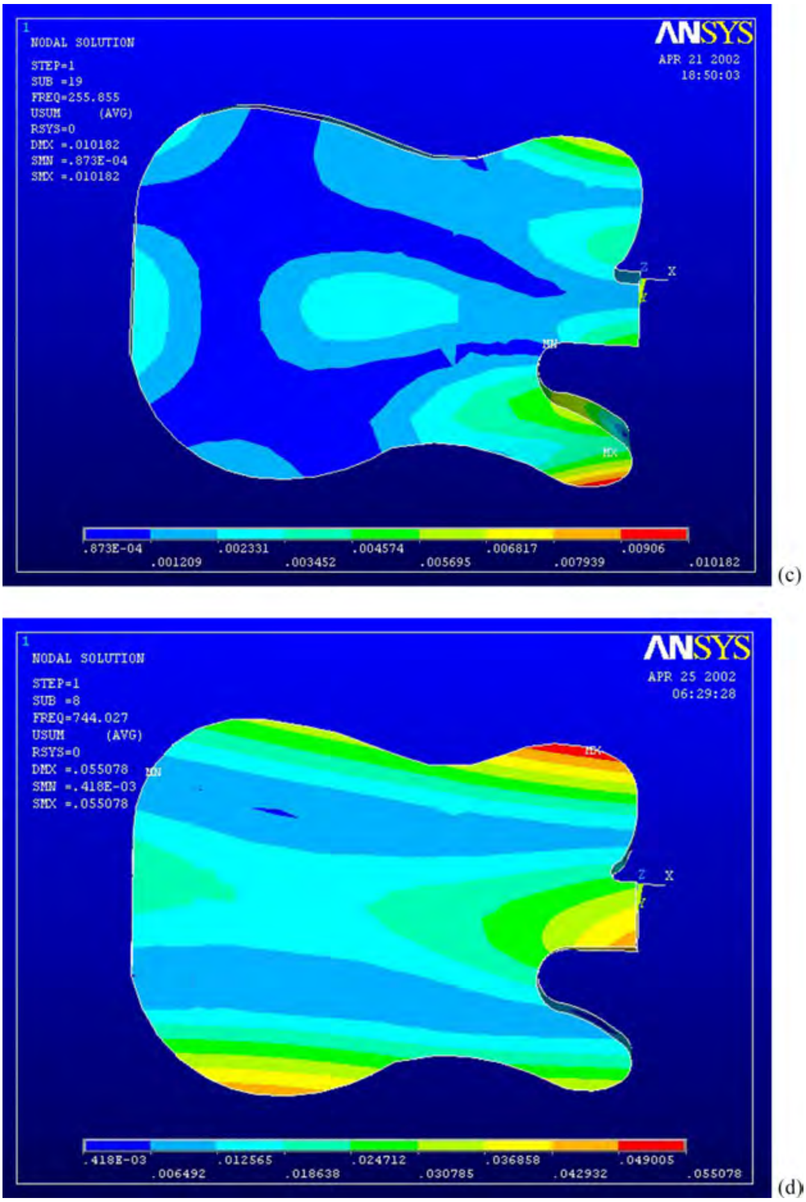

Figure 5.12. (Continued.)

explains Mike. A larger soundboard also makes the guitar louder, he adds, because the bigger it is the more air it will move as it goes backwards and forwards.

By contrast, electric guitars split up the two functions of selecting a note and projecting the sound outwards. The strings vibrate when an electric guitar is played, just as they do in an acoustic guitar. But rather than the vibrating strings setting up vibrations in the body of the guitar there is a 'pick-up'—generally consisting of a magnet with some wire wrapped around it—that detects the movement of the strings and converts the vibration into an electric current. The pick-up then sends a signal down a cable to an amplifier which is connected to a loudspeaker which outputs the sound. (See box 5.5 for more on pick-ups.)

The sound from an electric guitar is always produced by amplification rather than the vibration of the body. But different types of electric guitars sound different partly because some of the frequencies their strings vibrate at do in fact cause the body to vibrate, (see figure 5.12) causing the strings to lose energy at these sound frequencies, says Mike, whose research team has carried out experiments on electric guitars.

In one study different shapes of guitar bodies were observed absorbing different frequencies. 'Some guitars have a reputation for sustaining notes longer than others and the work we did seemed to indicate that although they appear to sustain notes for longer, actually they don't. If you pick a note on any musical instrument, because of the amount of energy that is contained in high frequencies a high note will fade away more quickly than a low note. The guitars that had a reputation for sustaining for a lower amount of time had more of the higher frequencies because they weren't losing the high frequency components [via being absorbed] and so a lot of the volume was disappearing fairly quickly,' explains Mike. 'The guitars that sounded like they were sustaining for longer simply didn't have the high frequencies [as they were being absorbed] so therefore you only heard the longer sustaining components.'

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Weblinks

You Tube video showing How To Tune Drums - by DW's John Good

You Tube video of Vater Drumstick Factory Tour showing how their drumsticks are made and tested

Animations of the Vibrational Modes of a Circular Membrane by Dan Russell, Professor of Acoustics at Pennsylvania State University.

You Tube video of a Circular Membrane (drum head) Vibration at different frequencies by Dan Russell

You Tube video of a drum solo by Larry Crockett from 2013

You Tube video of Larry Crockett playing for Eric Bibb at Glastonbury in 2008

You Tube video from New Scientist Cyborg Drummer creates unique beats

IOP Concise Physics

Outside the Research Lab
Volume 1: Physics in the arts, architecture and design
Sharon Ann Holgate

Chapter 6

High-tech trends—physics techniques used to create fashion and footwear

6.1 Introduction

When we get dressed each day, we probably don't pay much attention to the way our clothing and footwear is made. But the manufacturing processes used to make many mass produced garments rely on physics-based technology. Designers are also embracing physics phenomena and techniques to create innovative clothing and footwear for customers looking for alternatives to high street fashions.

In this chapter, thanks to textile designer Helen Paine, and process engineer Ian Jones, we will discover how machinery—including equipment based on ultrasound and lasers—is used to weld seams in fabrics. Helen will also reveal how computers help create most of the knitwear we buy, as well as describing a new type of composite fabric that she has developed.

We will then see some of the clothing by fashion and material designer Amy Winters, whose garments have been used in TV adverts and music videos. Amy has used fibre optics, electronics, and an innovative 'polymer opal' fabric that creates colour via diffraction in her designs. This polymer opal material was created by researchers from the NanoPhotonics Centre at the University of Cambridge, and physicist Chris Finlayson from Aberystwyth University, who works with the Cambridge team, reveals how these polymer opals are made.

Finally we will hear what physics-based technologies are being used by shoe designer Chau Har Lee to help create wearable shoes from unusual materials via specialist manufacturing methods including 3D printing.

6.2 Using physics based techniques to create seams

If we make a garment ourselves, we are most likely to sew pieces together to create the required shape. But as textile designer Helen Paine reveals, for certain types of shop bought clothing either removing the need for separate pieces, or using seaming

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techniques based on physics, is the norm. Helen, who specialised in knitted textiles and worked with printing and knitting technologies for her MA degree at the Royal College of Art (RCA) in London, says the mass production of knitwear is often carried out on industrial knitting machines controlled by CAD files.

‘The majority of cheaper knitwear is “cut and sewn” [which means] pieces of knitted fabric are produced that are then cut and sewn together. That’s how the shaping happens. But if you look at some garments you’ll see that they have little gathered marks around shaped areas such as arm holes or collars. That indicates the transferring of stitches to create the shaped areas,’ explains Helen. While very intricate work can be carried out on hand operated machines that require skilled operators, she says shaping can also be done via CAD controlled industrial knitting machines. ‘Whole garment technology’ creates the entire garment as one piece and so avoids seams altogether.

‘With sports lingerie and high-end sportswear, the stitching and the shaping of the garment for things like bra cups can all be made through the knitting process. By removing seams you’re improving comfort because these are clothes that are worn really close to the body. Stitched seams can be quite heavy and bulky because you’ve got extra thread, and often you’ve got reinforcement tapes. But when things are knitted in one piece there is smoothness,’ says Helen.

In terms of her own knitwear designs, Helen explains that for the final project of her Master’s degree in 2011, she developed a new textile with a unique surface finish by screen printing onto her knitted textiles a type of foam known as puff binder—which expands when heat is applied—to create a coating (see figure 6.1). ‘So I produced an almost laminate, composite material,’ she says. (For more on composites see box 2.5 in chapter 2.)

‘I was interested in coming up with something that was new aesthetically, but through that work I began working with and developing new technologies,’ continues Helen, who is currently taking a PhD researching and developing new joining technologies for garments at the RCA. Most of her PhD, she says, has involved working with stretchy fabrics ‘which relate very closely to knitted fabrics’.

Her current doctoral research is focussed on helping to develop laser welding techniques so they can be used to create seams and functional surface effects in stretch fabrics. ‘I am interested in pushing the boundaries of technologies. Laser welding is an interesting technology that is widely used for thermoplastics [see box 6.1 for more on thermoplastics], but it has been developed significantly by TWI (The Welding Institute), the company who sponsored my PhD, [for use in clothing],’ explains Helen.

‘Ultrasonic techniques, and adhesives and hot air welding equipment are also widely used [for creating stitch free seams],’ says Helen, explaining that some underwear and sportswear is bonded rather than being stitched using a similar process to that used on waterproof garments. (See figure 6.4 for an example of bonded sports underwear.)

‘The original cause for the development of these techniques was Macintoshes and outdoor clothing for workmen. Sealed seams were created because once you stitch a seam you’re repeatedly perforating it,’ explains Helen. One method of creating a

Figure 6.1. Knitted garments designed by Helen Paine made from the laminate textile she developed during her Master's degree at the Royal College of Art in London in 2011. (© Helen Paine. Reproduced with permission.)

waterproof seam, she says, is to stitch the seam and then apply an adhesive tape to the back of it using hot air welding equipment. This melts the adhesive, which is then cured by applying pressure to the seam. 'So it's a two-step process that seals it, but also simultaneously strengthens it.'

Helen feels ultrasonic welding—which is used in the manufacturing of outdoor products such as tents and lilos—and laser welding are a step on from using hot air bonding because they do not require adhesives. 'That reduces costs, and is more

Box 6.1. Thermoplastics

Artificial polymers are commonly called ‘plastics’, and they have many different applications from waterproof garments to drinks packaging. Polymers that become soft when they are heated, and only harden up if they cool down are known as thermoplastics. Widely used thermoplastics include PVC, polystyrene and PTFE. Most types of thermoplastic are reasonably soft and flexible at room temperature, but become softer and more pliable if they get hotter. Thermoplastics behave like this because of their structure.

All polymers are solid materials made from very large molecules, which are themselves composed of many smaller, identical building blocks of molecules known as monomers. A 2D diagram of the polymer polyethylene (which is commonly known as polythene) together with its monomer ethylene is shown in figure 6.2.

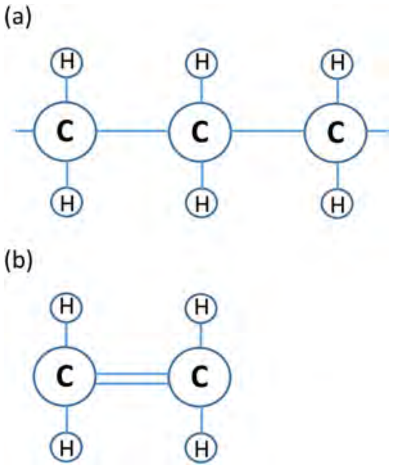

Figure 6.2. (a) A 2D representation of polyethylene, which is more generally called polythene. Each ‘C’ represents a carbon atom, while ‘H’ depicts hydrogen. (b) Polythene’s monomer ethylene. Polymers made up from carbon and hydrogen are known as hydrocarbons.

However there are three main ways—linear, branched and cross-linked—that these long chains can be arranged (see figure 6.3), each of which creates different polymer properties.

Thermoplastics consist of either linear or branched polymer chains. The types of thermoplastics used for clothing are made up from linear polymer chains. These chains can slide past each other easily because they are randomly arranged like noodles in a bowl, and are held together by either van der Waals bonds or hydrogen bonds which are both relatively weak types of atomic bonds. The ability for the chains to move readily is what gives these thermoplastics their flexibility.

By contrast the side branches of branched polymer chains (see figure 6.3(b)) are covalently bonded—in a covalent bond a pair of electrons is shared between two atoms—which is a much stronger type of bonding. This makes it harder for the chains to move past one another, and so produces a stiffer, stronger polymer.

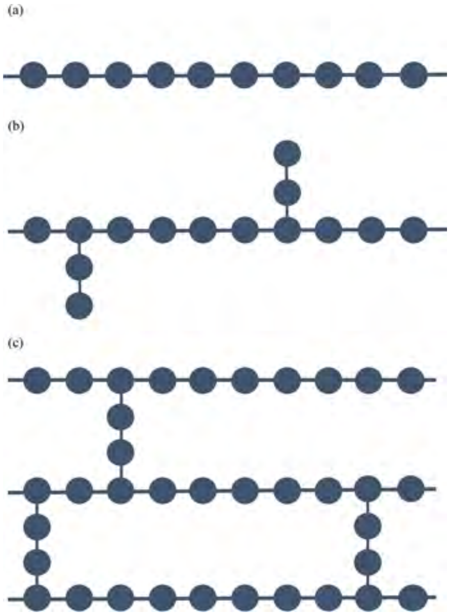

Figure 6.3. (a) a linear polymer chain; (b) a branched polymer chain; (c) a cross-linked polymer chain.

The stiffest polymers consist of cross-linked polymer chains (see figure 6.3(c)). These chains are unable to slide past one another at all as their cross-links are made up of covalently bonded atoms, and so the chains are held together with strong covalent bonds. Thermosetting plastics, also known as thermosets, are cross-linked polymers. Unlike thermoplastics, themosets cannot be softened and reshaped so cannot be recycled.

While materials like polythene and PVC are artificially created, many natural polymers that can be used to create clothing also exist. These include cotton, leather, rubber, and wool, as well as cellulose, which the cell walls of most plants is mainly comprised of. The textile industry makes viscose fabric from cellulose, so this polymer is widely used within fashion.

sustainable and ecologically friendly,' she explains. (See box 6.2 for more on laser welding and ultrasonic welding.)

6.3 Integrating physics phenomena into fashion design

London based fashion and material designer Amy Winters, who has exhibited at Fashion Week in both London and Paris, as well as in Las Vegas and Washington in the US, has experimented with a range of technology based fabrics and wearable electronics through her Rainbow Winters label. (See figures 1.2 and 6.9 for examples

Figure 6.4. Marks and Spencer's Infin8™ sports bra was created 'to achieve an increased balance of support and comfort during exercise. Backed by research from Portsmouth and Loughborough Universities, the Infin8™ sports bra features a figure of 8 supportive section, bonded to the inside of the cups. This limits motion and provides targeted support where it is needed instead of an all over compression. Unlike traditional sports bras that compress the breast, the Infin8™ sports bra allows more movement and comfort during running and active sports.' (Images courtesy of Marks and Spencer. © Marks and Spencer, 2016.)

of some of her designs.) While at the time of writing this book she is back at university taking a PhD in interactive textiles and soft robotics at the Royal College of Art (RCA) in London, and working on developing her own material, for Rainbow Winters Amy has created a range of one-off creations that have been used for advertising campaigns and music videos. She also produces retail ready-to-wear garments.

Amy says she first became interested in using emerging technologies in her clothing after training as a theatre designer at Central St Martins and creating costumes that ‘could tell a story or be interactive. If you added interactivity into the materials you could create an experience for the audience.’ She began by simply putting some Christmas lights onto a dress for an opera in 2006, then later moved on to collaborating with the smart textiles research lab at St Martins working with interactive textiles.

After completing her degree, Amy saw a business opportunity for creating clothing using these ideas. ‘Once you go into the real world that’s when the learning really begins. I didn’t want to study any more. I wanted to work with scientists,’ she

Box 6.2. Laser welding and ultrasonic welding

Welding techniques can only join thermoplastic materials, such as those composed of nylon, polyester or polypropylene fibres because the material around the join has to be able to be melted together, says Ian Jones, Principal Process Engineer at TWI (The Welding Institute) Ltd in Cambridge in the UK. He explains that this extends to plastic coated fabrics, so welding can be used to join the component pieces of tarpaulins or inflatable boats made from polyurethane or PVC coated fabrics. ‘Laser or ultrasonic welding may also be used to melt an adhesive layer between two otherwise un-meltable fabrics. This way, natural fabrics or dissimilar combinations may be joined,’ he adds. (Figure 6.5 shows a close-up of a laser welded seam, and figure 6.6 shows an ultrasonic and laser sewing machine.)

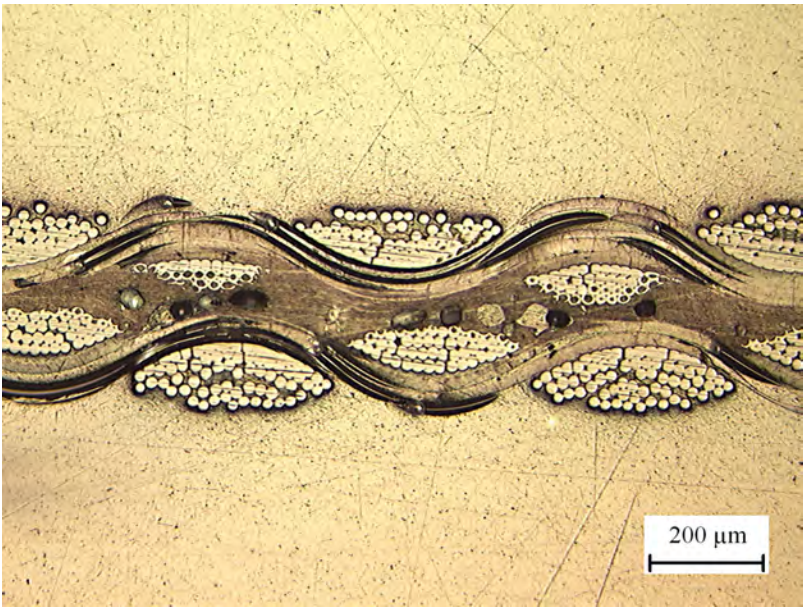

Figure 6.5. Reflected light optical microscope image of a laser weld in woven nylon fabric. (Courtesy of TWI Ltd. Reproduced with permission.)

Figure 6.6. An ultrasonic and laser sewing machine for garments and similar sized textile and film products. (Courtesy of TWI Ltd. Reproduced with permission.)

‘Ultrasonic welding, which was first used for plastics in the 1960s, is starting to be used for the seams in waterproof garments, so that the holes made by stitching and the seam taping stage can be avoided. The process is also used for swimwear and some other sports clothing where a flat seam is preferred. Laser welding [which entered commercial use for plastics in the 1990s] is not yet widely used for textiles joining, but demonstration garments and pieces have been prepared including a fleece jacket, waterproof jacket, and patterned pieces for scarves and dresses. In the latter case the laser has been used for laminating two fabrics, generating a pattern where one is melted to the other. This can avoid the use of certain chemicals and adhesives, normally applied for lamination,’ continues Ian.

In garments, these processes can be used instead of stitching for several reasons, says Ian. ‘Welding is faster in some materials, avoids a second step for water or air tightness, and sometimes allows for automation of the making process. A welded seam also looks very different from a stitched seam, providing aesthetic reasons for process selection,’ he explains.

If a mechanical vibration has a frequency beyond that which we can hear (above approximately 20 kHz), it is known as ultrasound. ‘Ultrasonic welding is carried out by applying mechanical impacts [to two pieces of plastic sited] between two metal fixtures or rollers at a rate of 20–40 kHz. (See figure 6.7.) These generate heating through friction between the two pieces of plastic and within the plastic (visco-elastic heating) when the material is distorted and released at a faster rate than it can recover elastically. In textiles the fibre contact points act as energy directors, rapidly initiating heating and melting at those points first. There is then movement of molten material, further visco-elastic heating of the molten material and spreading of the melt to the whole area between the rollers. The material re-solidifies quickly after passing through the rollers to complete the joint,' explains Ian, adding that at the molecular level the mechanisms of heating by ultrasonic welding and laser welding are quite different.

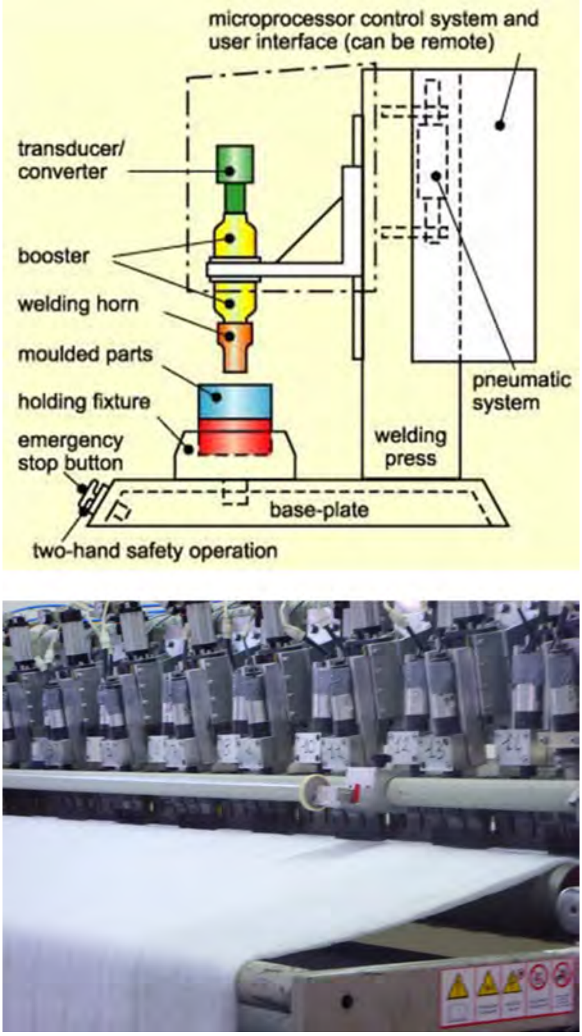

Figure 6.7. (a) Diagram showing the main parts of an ultrasonic welding machine; (b) an ultrasonic drum quilting machine. Outdoor jackets, for example, can be made from quilted fabrics. (Courtesy of TWI Ltd. Reproduced with permission.)

'Laser welding (see figure 6.8) does not use mechanical vibration, but relies on the absorption properties of the plastics or additives in the plastics to generate heating. Photons of a suitable energy or frequency are absorbed by initiating vibrational modes (stretching or bending), in the molecules of the polymer or in specially added dyes or pigments. The molecular vibration raises the temperature of the plastic, and, under the right control, leads to melting. Overheating, leading to damage and splitting up of the polymer chains is avoided by controlling the power of the laser applied and the speed of processing. The molten fibres are pressed together and rapidly cool once the laser has passed,' says Ian.

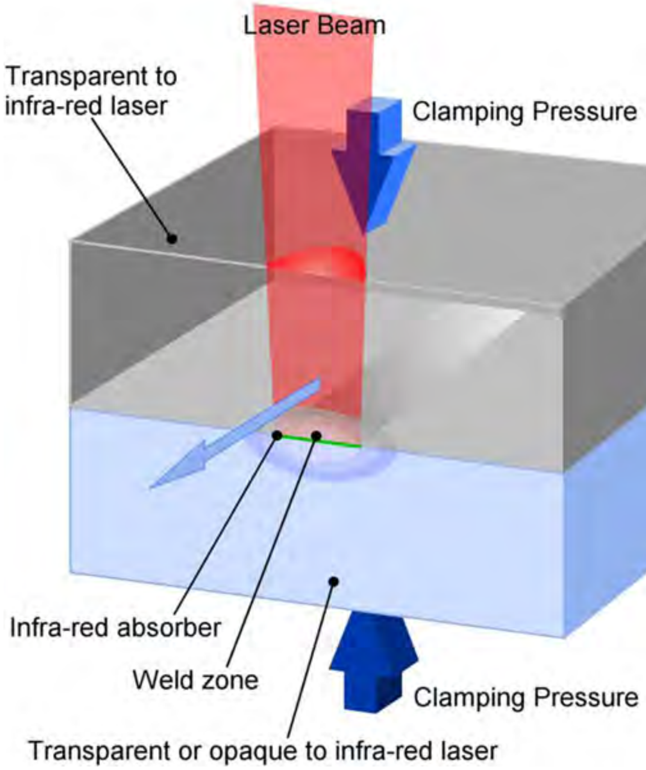

Figure 6.8. A schematic diagram of the laser welding process. (Courtesy of TWI Ltd. Reproduced with permission.)

'In both [laser and ultrasonic welding] the final mechanism of joining is molecular chain entanglement through inter-diffusion of the polymer chains,' continues Ian, adding that this part of the process is only possible because the polymer chains are mobile when the plastic is molten. This, he says, is in contrast to thermoset polymers, in which the chains are linked together and are not free to move when they are heated. Other methods such as adhesive bonding are used to join these types of polymers.

says. Her first project was funded by the Technology Strategy Board and involved working with a colleague to create holographic, laminated leather. Her colleague made bags from the leather which were sold in Selfridges, while Amy decided to create fashion garments from the material.

‘Fashion is really exciting because it is body based, which is a really nice platform to develop materials for because it is interactive, imaginative and visual. Fashion is also a great communications tool which affects everyone in some way,’ she says. ‘My textiles do perform, but although applications are not necessarily for celebrities or the stage, the inspiration for them definitely comes from the theatre.’

Amy’s first prototype garment was a battery-powered sound reactive ‘thunderstorm’ dress (see figures 1.2 and 6.9(a)). Following the success of the prototype, which was exhibited in Milan at the ‘Made In Future’ exhibition, Amy made another battery powered thunderstorm dress which reacted to volume and was used by Stoli Vodka for an advertising campaign. ‘Both garments were based on the same concept, which is bespoke-made electroluminescent panels, a sound sensor, and a microphone integrated into an inverter [a device that converts direct current (d.c.) into alternating current (a.c.)],’ explains Amy. The electroluminescent panels were quite bright, and she says preferable to LEDs for showing graphics as they avoid the dot matrix effect produced by LEDs. (See box 6.3 for more on electroluminescence.)

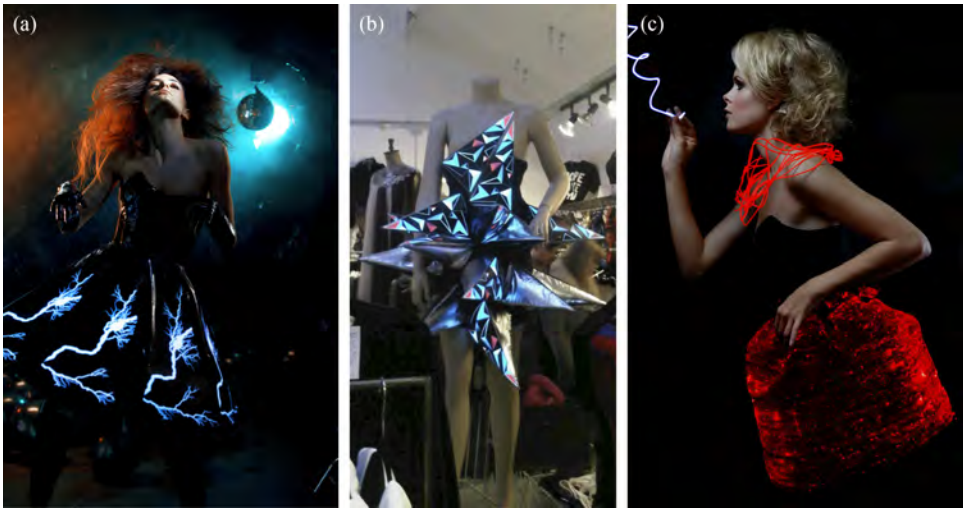

Figure 6.9. (a) Thunderstorm dress by Amy Winters with bespoke-made electroluminescent panels and an embedded microphone and sound sensor. (Photograph © Amy Winters, reproduced with permission.) (b) Picasso explosion sound-reactive dress by Amy Winters. This dress is made from neoprene and electroluminescent panels, which light up in white, blue and red in response to sound. (Photograph © Amy Winters, reproduced with permission.) (c) Dress by Amy Winters made from a fibre optic woven fabric. (Photograph © Amy Winters, reproduced with permission.)

Box 6.3. Electroluminescence

All types of luminescence involve the emission of light from a substance that has not been heated up. The different types of luminescence get their names from whatever causes the luminescence. For example, chemiluminescence is generated by chemical energy, sonoluminescence by sound waves, and bioluminescence (such as that given out by glow worms and fireflies) by biochemical energy.

Electroluminescence is the emission of light from substances as a result of a voltage being applied. Electrons from the applied voltage give energy to the atoms of the electroluminescent substance. The atoms then emit this energy back out as light when they return to their original, lower energy state (known as the ground state).

To create an electroluminescent panel, the electroluminescent material is sandwiched between two transparent plates that act as electrodes. When the electrodes have a voltage applied across them, the electroluminescent material emits light.

‘The thunderstorm dress generated so much publicity that I wanted to create a saleable product out of it. It had cost so much to make it was not a viable commercial option, so I decided to create a version using off-the-shelf photochromic ink,’ she continues. This ink responds to sunlight—which changes the white printing on one of her dresses to a pink-purple—and has been used in spectacles. ‘I wanted to go down this route because it can be hand printed onto silk and cotton, is dry cleanable, and there is no need for electronics,’ says Amy.

As part of her PhD, Amy is now trying to develop a more sophisticated version of the original electronic garment that is easier to wear. ‘Electronics has changed so much and become less bulky now. The thunderstorm dress was only 2010, but it seems like a different world as the batteries were so bulky. I’m now exploring techno-reactive composites, microphones as small as my fingernail, and micro-sensors. Textiles are all about the form factor. Everything needs to be seamless and beautiful. So the tinier the components, the more aesthetic the end garment will be,’ says Amy, adding that the ‘holy grail’ is to embed electronic components at the fibre level so they cannot be felt by the wearer. This, she feels, is key to large-scale consumer take-up of interactive garments. ‘As long as people can feel something, or have a battery pack, it is slightly off-putting,’ she states.

‘At the RCA I read a lot of scientific papers that I then try to apply to my research by reverse-engineering processes. That’s been a really exciting journey. It is a different design process,’ continues Amy, who has collaborated with laboratories on her designs, including the NanoPhotonics Centre at The University of Cambridge.

The Cambridge team had developed a polymer opal, and Amy met the researchers in 2012 after they spoke at a scientific conference. ‘I go to a lot of scientific conferences to see what types of materials are out there. They had heard of my work previously, and we started to collaborate,’ she explains. This

Figure 6.10. Fashion garment made out of polymer opal, designed by Amy Winters for the 'Structural Colour' collection for her Rainbow Winters label. (Photograph © Amy Winters, reproduced with permission.)

collaboration, which Amy says she found 'really exciting', led to her 'Structural Colour' collection (see figure 6.10 for an example). This uses stretch fabrics made from a film of polymer opal which she cut to size and then applied via a heat press to the garment. 'Unlike inks which contain pigment, this is a structural colour that is created by diffraction,' says Amy. (See box 6.4 for more on the Cambridge polymer opals.)

Amy has seen the field of wearable technology 'accelerating very fast' since she began her PhD in 2013. 'Larger [high street fashion] companies are investing in fashion tech, and seeing the business value. It is still led by niche designers like me, but I think the niche designers are starting to collaborate with larger companies and it is becoming more mainstream,' says Amy. She predicts that by 2018 we are likely to see fashion with embedded technologies hitting our high streets and malls with accessible price tags thanks to economies of scale, and suspects the 'early adopters' of wearable technology will be predominantly young.

'There is a big demand for stylish pieces which fit that demographic because the wearable tech pieces already available don't really appeal to a teenage or early twenties consumer. But if it was really thought about and the price point was acceptable then I think the market is there. It's just a case of thinking about the technology and the design, and doing it in a way that fits in with that demographic's lifestyle,' she feels.

When Amy designs, she says she doesn't just think about the visual impact of her pieces. 'I'm also thinking about the sensation and feeling, emotion, sensitivity and tactile qualities. These are part of the aesthetics, but also part of how a human interfaces with the material. It's that space that I'm interested in.'

Box 6.4. Polymer opals

The polymer opal fibres and thin films created by Jeremy Baumberg and colleagues in the NanoPhotonics Centre at the University of Cambridge are stretch-tunable, which means they change colour when they are twisted or stretched. This ability is thanks to the structure of the polymer opals which is created via a processing method they developed, as Chris Finlayson, a lecturer in physics at Aberystwyth University in Wales who collaborates with Jeremy, explains.

The starting point, says Chris, is sub-micrometre sized spheres made from common materials such as polystyrenes and polyacrylates (see figure 6.11(a)). These spheres, which are all roughly the same size, are initially in a random arrangement (see figure 6.11(b)). To make a stretch-tunable film (see figure 6.11(c)) or fibre (see figure 6.11(d)) they need to be arranged into a regularly repeating, ordered pattern, which is achieved via the new processing methods.

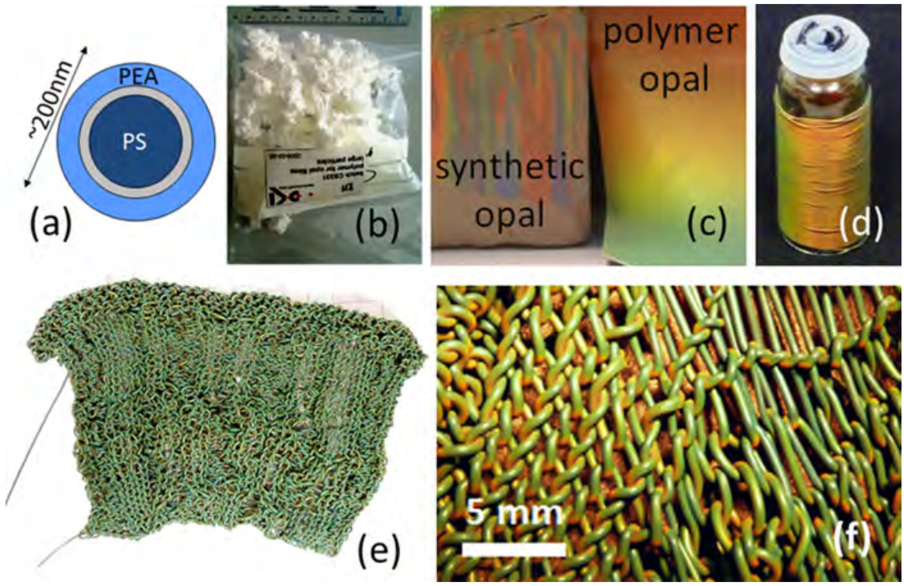

Figure 6.11. Polymer opals created by Jeremy Baumberg and colleagues at the University of Cambridge. Part (a) represents a cross section through one of the polystyrene(PS)-polyethylacrylate (PEA) spherical particles used to produce polymer opals, while (b) shows the raw material as obtained from the supplier which can be processed into thin films (c) or extruded into fibres (d). Image (e) shows a fabric knitted from polymer opal fibres, which changes colour when stretched as the close-up view of the fabric in (f) reveals. (Courtesy of Jeremy Baumberg, NanoPhotonics Centre, University of Cambridge. Reproduced with permission.)

'Polystyrene spheres have a kind of "sticky" mutual interaction with each other—they are coated in a soft gum-like polymer—so the main processing [step] is what is known as shear ordering. They are disordered when they come out of the polymer extruder so [to create a film] we have to find a way of inducing them to arrange into an ordered pattern. We press the material into a thin film to start with and then we apply a shearing force by passing the film over some kind of apex or heated edge. As you do that, you're generating local shear forces between the particles in the film. (See box 2.1 for more on shear stress.) The particles are stuck together by this gum so we're stretching them apart by stretching the gum,' explains Chris, adding that this stretching allows the spheres to slide past each other and reconfigure themselves.

'The spheres also come together again as there's a relaxation of those elastic forces that have built up, so it's almost like you've annealed out any disorder there and they come together into a more energetically favoured configuration [which is more ordered]. In each pass over the [heated] edge the particles tend to want to find a more ordered configuration. So you can repeat the process many times and you generally see the ordering of the spheres improving as you go. What you ideally want is for them to be in a perfect crystalline ordering [which has a regularly repeating pattern] at the end of the process,' says Chris.

As the structure changes from a relatively poorly ordered ensemble of spheres into one that is very highly ordered the optical properties change. Before the processing, when there is a big variation in the average distances between spheres, the polymer film has a white, milky appearance with very little colour. After processing, when the spheres have been ordered into a crystalline-type pattern, there is a very regular distance between the individual spheres in the film and when it is moved through certain angles and directions vivid colours appear.

These colours are the result of beams of daylight (or artificial 'white' light) falling on the regular pattern of spheres and being separated out into a large number of light beams which each have a different wavelength. This process is known as diffraction, and the colours we see are thanks to beams with that colour's wavelength interfering with each other 'constructively' and so combining together to produce a bright beam. The colours of any light beams that interfere 'destructively', and so cancel each other out, will be missing from the spectrum. Tilting a CD around in your hand and looking at the side the data is saved on will reveal a similar effect.

Both CDs and polymer opals produce what is known as 'structural colour' says Chris. '[We] looked at how we could optimise the processing conditions to give us the greatest degree of this so-called structural colour that derives from the periodicity of the lots of sub-micron [micrometre] sized balls. We were getting them to order [in a regular pattern] on the same length scale as the order of the wavelength of light, which is why they show these very interesting diffractive properties and colour phenomena that we see,' says Chris.

In addition, the end product thin-films can generate further colours when they are 'stretched tuned', in other words their colours are changed by stretching, twisting and bending. (See figure 6.12.) The stretching causes the spacing between the planes of regularly spaced spheres to change. But unlike during processing, which takes place at a higher temperature so that the polymer behaves like a viscous liquid, this stretching produces completely reversible effects.

Using different sphere sizes (between 150 and 300 nm diameter) enables the researchers to make the polymer opals in different end product colours which will then show a specific range of colours when stretched. For a red opal, for instance, as the strain increases the structural colour tunes towards the green and the blue.

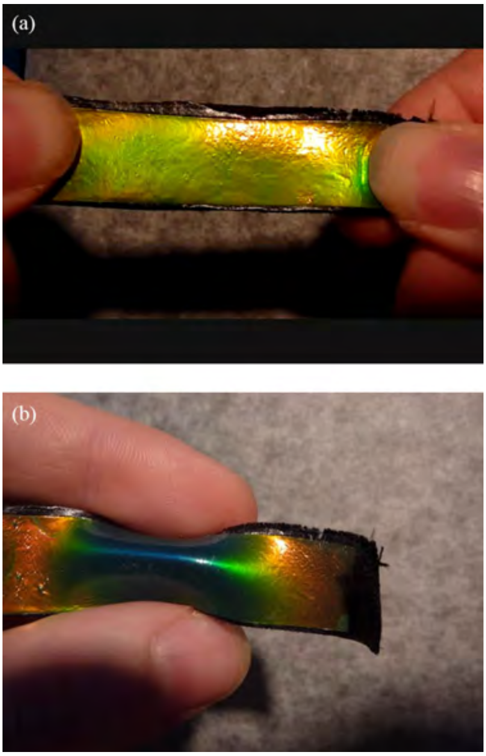

Figure 6.12. (a) and (b) A 50 μm thick polymer opal film on a black elastic fabric backing. As (b) shows, the film is 'stretch-tunable', which means that it changes colour when it is twisted or stretched. (Courtesy of Jeremy Baumberg, NanoPhotonics Centre, University of Cambridge. Reproduced with permission.)

The researchers have also created fibres (see figure 6.11(d)–(f)) that have similar optical properties to the thin films. 'With the fibres, we take the material we get from the chemist and put it through a high pressure polymer extruder. The mix of the particles with their gum like shells get forced out of a small circular aperture at high pressure,' says Chris. To some degree the particles will also form ordered arrays during that extrusion process, he explains.

While various researchers had been experimenting with synthetic opals since the 1970s, thanks to work by this team the processing has now been optimised such that these polymer opal materials can be produced on a very large scale, as detailed in a 2016 *Nature Communications* paper (see references). 'If you are interested in decorative applications, or clothing, or mass production as an anti-counterfeit measure [for banknote security] the reproducibility at scale-up is critical,' says Chris, adding that they are continuing to investigate the viability of attaching polymer opals to fabric on an industrial scale as well as seeking other end uses for the technology.

6.4 Physics-based technologies used in footwear design and manufacture

London based shoe designer Chau Har Lee creates shoes for her own label—which have been sold in Selfridges in London—from a range of materials not often seen in footwear (see figures 6.13 and 1.3). Chau says her designs are inspired by a mixture of things.

'I trained in a conventional, traditional way. I went to Cordwainer's College and learned various shoemaking construction techniques, and I absolutely loved it,' explains Chau, adding that at first she worked for a company who created handmade shoes. 'It was only when I went to the Royal College of Art (RCA) to do my Master's degree that I decided to venture outside of the world of leather. I was very comfortable with leather in many different forms—working on shoes, with handbags and with leather interiors. I was learning lots of different skills, and when it came to [starting] my Masters I sensed there was a way to combine them, but I couldn't work out how. So firstly I stayed within the leather realm but just experimented with various ways of shoe making. Then mid-way through my degree I thought, "What's the point in not challenging myself further?"'

Chau decided that as she was part of the RCA, and had access to different facilities, experts and seminars, she would seek out experts in different fields such as woodwork and jewellery and ask their advice on what materials would be viable to use in a new collection of shoe designs.

'For instance I was talking to jewellers about what metals would be best to use in terms of being able to perform as a heel. Usually a heel is made from plastic which has a hardened metal rod going through it to give it support. I wanted to experiment with metal, to see if there was a way I could use it stripped bare without the plastic,' explains Chau. She says that particular project was 'amazing in terms of finding out how to use metal, and how pliable it was, its strength, and then how to finish it because it goes from being such a crude kind of material to being such a beautiful and polished item which then looks like a piece of jewellery.' The result of this work—a design with a laser-cut stainless steel heel that was sold on a made-to-order basis in Selfridges—can be seen in figure 6.13(b) and (c).

This shoe, says Chau, was born from a 'lot of experimentation and trial and error', beginning with a paper template that she put around her foot. 'With this collection I tried to forget what I knew about traditional shoe making, and see if there was a different way of doing it. I started with paper or card and scissors, and tried to create a structure [from cut-out pieces of the paper or card] which might work in terms of actually holding the foot. This gave me some idea of proportions, height and space, and the general fit on the foot'. In some cases it took Chau days of making continual attempts at the design to get the shape correct.

For the metal-heeled shoes Chau says she 'wanted the steel heel to be as thin as possible so I experimented with heels in various thicknesses.' In each case she tried out walking in each version of the heel herself. 'If I fell down then I would know it wouldn't work!' she says. The resulting successful design has a 3 mm thick heel. 'The people who laser cut my heels usually work on large architectural metal structures,

Figure 6.13. Shoes by Chau Har Lee. (a) Prototype flat packed shoe by Chau Har Lee made from seven pieces of Perspex which slot together and do not require glue. (b) and (c) retail version of shoe by Chau Har Lee with heel made from laser cut and welded stainless steel. (Photo (a) by George Ong and photo (b) by Sylvain Deleu. All photos courtesy of Chau Har Lee. Reproduced with permission.)

as do the welders who weren't used to working on items as small as shoes. So we had to do a lot of refining to the welding because you see all the detail on the shoes,' says Chau.

In general, to try out heel designs for this collection, Chau initially sandwiched piles of cut out cardboard together to see if she could stand on it for a couple of seconds. This gave her an idea of whether a particular structure was likely to work. 'If the structure seemed sound and solid, then I could make it in another material and see how it would work. When I had something physical in front of me I could then take it to someone in another department and say: "I want to build this structure. Which material do you advise me to use?"' she explains, adding that the jewellery and woodwork experts could also recommend ways to alter the structure to improve its strength.

Chau also consulted the products department at the RCA, where she learned about 3D printing and rapid prototyping. 'That was a massive eye-opener. All of these things combined to push my work in a very different direction, and since then I've been very much inspired by furniture, buildings, innovative use of materials, and how things are constructed. I really love putting things together almost like a jigsaw puzzle. That's what I'm drawn to,' she says.

'I always begin working by hand with paper and scissors, or leather and a last [a wooden model that captures the overall shape of a foot, which is used for shaping shoes during manufacture and supporting them during repair]. For the 3D printed shoe (see figure 1.3) although I wanted to have a very simple structure I scanned a last so I had a 3D image of a last shape. I then built the shape [of the shoe] around that in CAD software,' continues Chau.

The resulting shoe, she says, is made up from layer upon layer of resin that is hardened from its liquid state by a laser that traces out the shape of the shoe one layer at a time. Once the shoe is completely built, all the unused liquid resin drains away (as shown in this video clip—figure 6.14). 'The shoe is very strong and the good thing about it being 3D printed is that it is made of one solid piece of resin so there are no joins.' This, explains Chau, eliminates the weak spots which would exist had the shoe been made from three different parts.

Chau says she uses computers a lot in her work now because CAD is being increasingly used in shoe design. She feels that the use of rapid prototyping for footwear via 3D printing is also likely to increase, despite being expensive. 'It opens up a whole new avenue for prototyping, as shoes can be built quite quickly and you have the finished result there which you can take away to be made in other materials.'

In her own work, she is constantly on the hunt for different materials to use. 'It has to be a balance between a material that is light enough, strong enough, and looks good,' says Chau, who finds that experimentation is something she never gets bored

Figure 6.14. Resin shoes by Chau Har Lee being 3D printed. Figure 1.3 shows one of the finished shoes. (© Chau Har Lee. Reproduced with permission.)

of. ‘I’m always thinking about how I can improve designs, and try new materials and different types of constructions. It is an on-going process.’ Chau particularly enjoys the multi-disciplinary nature of such an innovative way of working. ‘It is nice to be inspired by other disciplines and to collaborate with experts in their fields,’ she says, adding that this can lead to innovations for all involved in the collaboration.

‘There are constantly new and exciting technologies coming about, or technologies that are new to footwear,’ says Chau. ‘Now footwear designers are thinking out of the box and experimenting with different things, and that’s exciting. I think that brings a whole new dimension to footwear design, and a whole new aesthetic.’

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Holgate S A 1999 *The future’s pants,* Focus, pp 72–75

Zhao Q and Finlayson C E *et al* 2016 Large-scale ordering of nanoparticles using viscoelastic shear processing *Nature Communications* **7**, Article number: 11661

Weblinks

Amy Winter’s Rainbow Winters website which includes images and descriptions of her designs

Video of Chau Har Lee taking about her designs

Helen Paine’s work at the Royal College of Art in London

Shima Seiki knitting machines

Videos about the 2016 exhibition Manus x Machina: Fashion in an Age of Technology at The Met

Interview with the exhibition curator Andrew Bolton

Gallery views of the exhibits

IOP Concise Physics

Outside the Research Lab

Volume 1: Physics in the arts, architecture and design

Sharon Ann Holgate

Chapter 7

Building for the future—physics within sustainable and visionary architecture

7.1 Introduction

When a new public building is unveiled initial reactions to it will often be based purely on its external aesthetics. What may be less obvious are any sustainable features that are built into the structure. But in an era when environmental concerns are increasing, the ability of a building to use less energy than similar buildings is an important factor.

In this chapter we will explore the role of physics in the drive towards sustainable building thanks to Alex Hope, from Northumbria University, Newcastle, who has worked in the field of construction sustainability since 2008 first for local government then as a university lecturer. Alex talks about the commercial case for sustainability as well as revealing some of the innovative materials, and physics-based technologies that enable buildings to be environmentally friendly.

In addition, Guilherme de Oliveira e Silva from the Université Libre de Bruxelles in Belgium explains how together with colleague Patrick Hendrick he investigated the challenges for householders wanting to generate their own electricity—by using solar panels in combination with lead-acid batteries—rather than getting it from the grid.

Finally, with the help of Chair of Architecture and Landscape at the University of Greenwich London Neil Spiller, we will hear how concepts from physics, as well as physics-based technologies are shaping the thoughts of visionary architects. I first interviewed Neil for a BBC Radio 4 programme in which he discussed how biological processes might be used to inspire new methods of house building. In this chapter he reveals how ideas from nanotechnology, and the possibilities offered by augmented reality, have influenced his work.

doi:10.1088/978-1-6817-4469-8ch7

7.2 Sustainability

The first principle of sustainability is to design a building that does not need any energy, says Alex Hope, a Senior Lecturer in Business Ethics at Northumbria University Newcastle in the UK who previously spent four years as a lecturer in sustainable development and project management in Northumbria's Faculty of Engineering and Environment. 'Two thirds of the energy used in buildings is for domestic heating and air conditioning so you try to require less use of energy for heating and cooling through the design and the materials used,' he explains.

The use of particular materials and design methods is far from being a new concept. 'Roman bath houses had thick walls facing south which would heat up in the Sun and provide some of the indoor heating. We can replicate this idea today by building thick concrete walls, says Alex. Innovative materials are also playing a large part in improving building sustainability. For example, Alex says that there is a push to build solar panels into existing materials so that skyscrapers could generate solar power via panels embedded in their windows. (Box 7.1 reveals how solar cells work.)

Box 7.1. Solar cells

In box 2.4 on semiconductor lasers we saw how a p–n junction can emit light. It is also possible for a semiconductor p–n junction to detect photons of light falling on it. This requires a voltage applied across it in the opposite direction (known as reverse bias) compared with the voltage applied across the p–n junction in a semiconductor laser. Electronic devices based on this principle are called photodetectors or photodiodes. Each different type of semiconductor can only detect certain wavelengths of light, and silicon is one of the best materials for detecting sunlight so is used to make most solar cells.

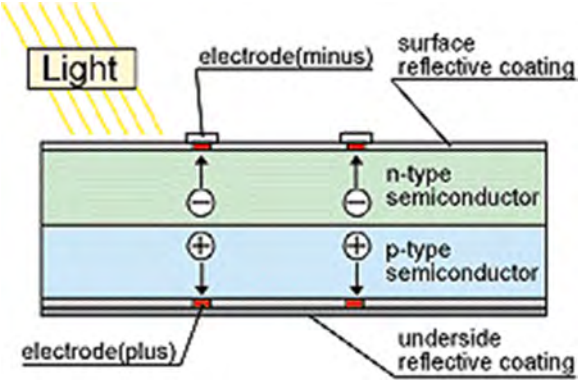

Figure 7.1. The main parts of a solar cell. The 'plus' symbol denotes a hole, and the 'minus' symbol represents an electron. (Courtesy of Kyocera Corporation. Reproduced with permission.)

Whereas in the semiconductor laser an electron recombining with a hole produces a photon of light, in a solar cell each photon from the Sunlight falling onto the device creates an electron and a hole, known as an electron–hole pair.

The current running through the p–n junction of the solar cell produces an electric field. This causes the electrons created on the p-side to be swept towards an electrode at the end of the n-side that connects to an external electric circuit. Conversely the holes created on the n-side move to the electrode on the p-side (see figure 7.1). The resulting current flow is known as the ‘photocurrent’ and is proportional to the intensity of the Sunlight falling on the solar cell.

Figure 7.2. Domestic solar panel installations in the UK. (a) Adjoining properties with solar panels fixed to south facing roofs. (b) Closer view of an 8-panel 1 920 kwh (per year) rated system with the panels wired in series, installed circa 2011. (Images © Dave Culpeck. Reproduced with permission.)

Solar cells are not particularly efficient at converting sunlight into electricity so lots of individual solar cells need to be joined together to create a solar panel that can produce a useful amount of electricity (see figure 7.2).

As well as being used to create power here on Earth, solar panels are also used to power electronic equipment on-board satellites and spacecraft. For instance, NASA's Juno spacecraft which was launched in 2011 and reached Jupiter in 2016 has three solar arrays totalling over 60 m^2 in surface area that are comprised of 18 698 individual solar cells. The total power output of these arrays when the spacecraft was near Earth was approximately 14 kilowatts, which dropped to around 400 watts by the time it reached Jupiter. (Figure 7.3 shows artists impressions of the Juno probe near Jupiter.)

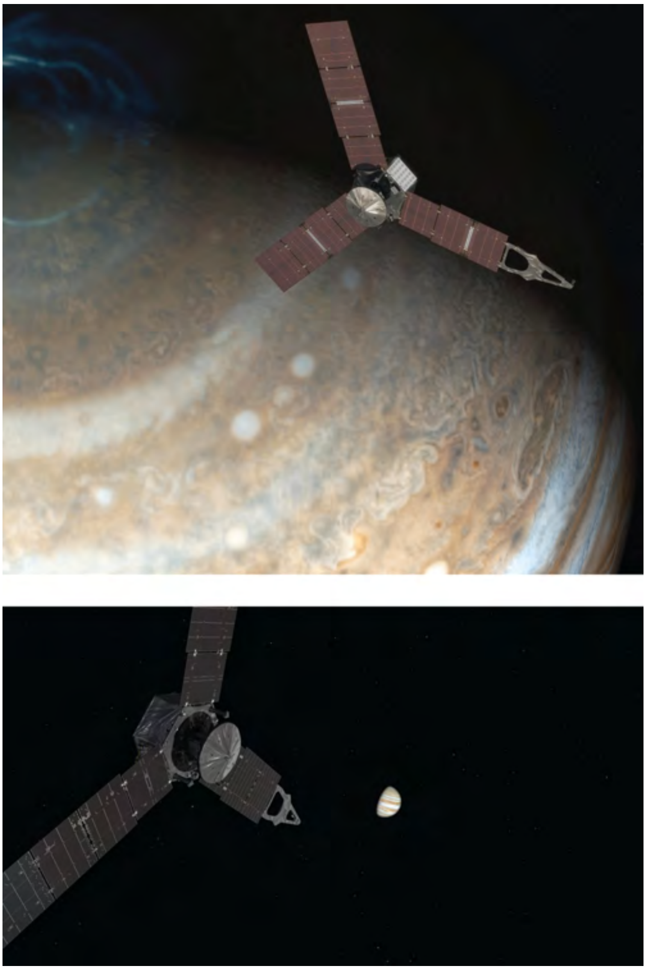

Figure 7.3. Artists impressions of the Juno probe near Jupiter, showing the three solar arrays. (a) *Juno Above Jupiter's Pole* (Artist's Concept). This artist's rendering shows NASA's Juno spacecraft above the north pole of Jupiter; (b) *Juno Approaches Jupiter* (Artist's Concept). This illustration depicts NASA's Juno spacecraft approaching Jupiter. (Image credit: NASA/JPL-Caltech).

'There is a lot of movement towards trying to use physics and chemistry to develop these kinds of smart building technologies,' continues Alex, who has been working on a project to retro-fit solar panels, triple glazing and biomass boilers into social housing and buildings for elderly people in the UK, along with a new type of insulation for domestic properties that is much thinner, more energy efficient, and cheaper than previously used insulating materials. 'We are using almost space age materials,' says Alex, adding that some social housing is now being built or retro-fitted with heat exchangers (see box 7.2) to help reduce energy costs for heating and cooling. (Figure 7.4 shows one of the sustainable new build projects Alex has worked on.)

Building sustainability is assessed against a set of criteria that cover social and economic factors, as well as energy physics says Alex, whose research areas include sustainable development, energy policy, and corporate social responsibility. In the US there is the LEED (Leadership in Energy and Environmental Design) certification from the US Green Building Council. (See figure 7.7 for an example of a LEED platinum building.) In the UK and 76 other countries around the world, buildings are assessed against BREEAM (Building Research Establishment's Environmental Assessment Method), which was the world's first standard for assessing the sustainability of buildings and infrastructure. BREEAM assessors evaluate buildings for a range of factors including carbon emissions reduction, and the life cycle environmental impacts of the construction materials used. As at the summer of 2016 there were 2 247 131 buildings registered for BREEAM assessment, and 546 000 certificates awarded worldwide.

Figure 7.4. Solar panels, double glazing, and LED energy saving light at the retirement accommodation Whinstone Lodge, in Whitley Bay in the UK. (© Dr Alex Hope. Reproduced with permission.)

Box 7.2. Heat exchangers

Heat exchangers transfer heat from one fluid (liquid or gas) to another. One of the simplest designs of heat exchanger consists of a container housing a series of tubes arranged parallel to one another which have one fluid flowing through them, while another fluid flows through the container around the outside of the tubes. In this type of design although heat transfers from the hotter fluid to the colder one, the two fluids do not come into direct contact with one another.

Figure 7.5. The SHARC sewage heat recovery system. (a) Diagram showing the fluid flow through a SHARC system installed in a house. (b)–(d) The SHARC system in the Sail Condominium Project at the University of British Columbia in Canada. This installation is producing hot water for the building as well as heating it via an under-floor heating system. It is generating 220 000 BTU every hour, and reducing carbon emissions by 100 tonnes a year. (Courtesy of IWS. Reproduced with permission.)

Heat exchangers can make use of waste heat generated by some other process—such as a furnace operating or an engine running—to heat areas such as the insides of buildings or vehicles that would otherwise require heating via another energy supply. For example, the SHARC sewage heat recovery system created by IWS (International Wastewater Systems) in Canada (see figure 7.5) uses the heat from raw sewage to provide hot water, as well as space heating and air conditioning for buildings. So far SHARC systems have been installed in buildings in Australia, Canada, the UK, and the USA.

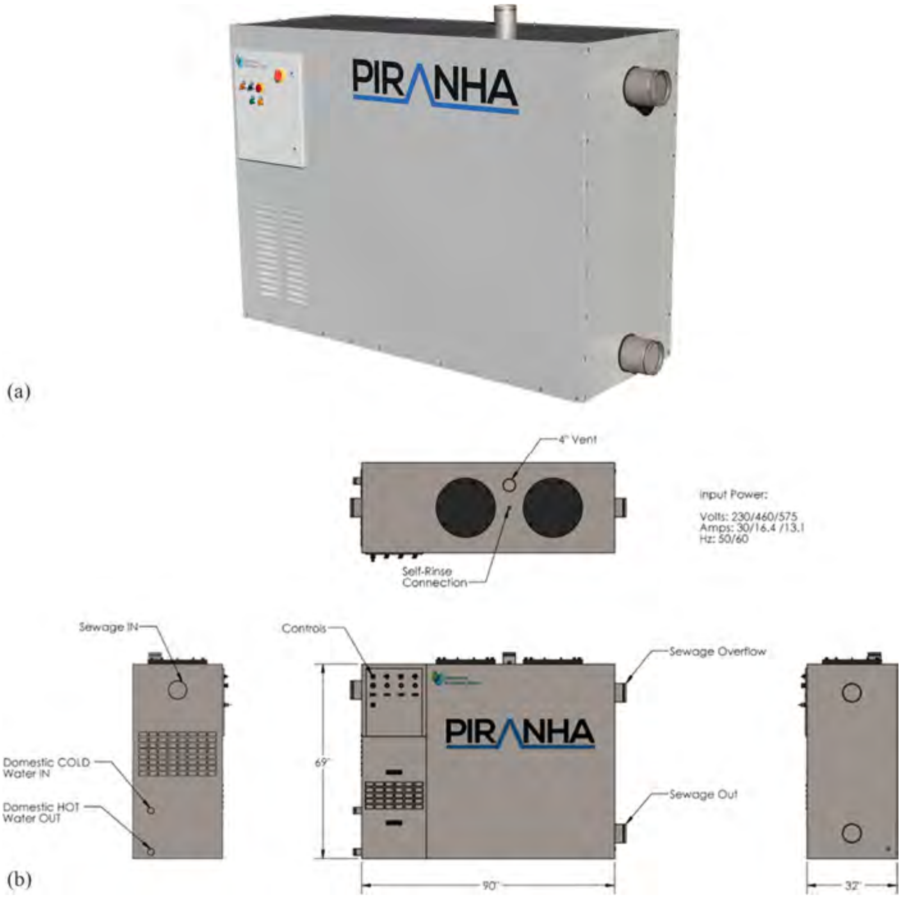

Figure 7.6. The PIRANHA sewage heat recovery system by IWS. (a) The heat exchanger unit which can provide 2000–4000 gallons of hot (up to 71°C) water a day for domestic hot water heating; (b) a diagram of the system showing the entry and exit points for the sewage. (Courtesy of IWS. Reproduced with permission.)

Inside the SHARC heat exchanger unit there are several metal plates stacked in parallel close together. While raw sewage—either from a residential building or an industrial process—flows along one side of the plates, clean water flows over the other side of the plates. This allows heat energy from the sewage to be transferred across the plates to the clean water which flows round in a closed loop. A second heat transfer process then occurs when the heated clean water transfers its heat energy to the building's heating or hot water systems. For hot water heating, for example, the water in the closed loop transfers its heat to cold incoming domestic water.

Before being pumped into the SHARC system, the raw sewage is captured in a tank and depending on the solid content in the sewage can also be filtered to separate out particulate matter down to 2 mm in size. The heat of this sewage depends on its origin (for example whether it is waste water from a brewery or human waste) and also on the climate. In general the sewage flowing down a sewer main from a residential building can be around 20 °C–22 °C in summer, and roughly 13 °C–16 °C in winter. Typically two or three passes of the heat exchanger plates are made by both the sewage and the clean water, and the flow is automatically reversed to help stop the build-up of small particles of sewage on the plates.

A more compact, cheaper version of the SHARC system known as the PIRANHA (see figure 7.6)—which was launched by IWS in 2016 and won the American Society of Heating, Refrigerating and Air-Conditioning Engineers Green Building Product of the Year award—has been designed for smaller buildings. This system differs from the SHARC by collecting smaller quantities of raw sewage in a tank, and containing a heat exchanger that allows direct transfer of heat from the sewage to cold water from the domestic supply. IWS are also working on developing an even smaller system for individual homes that they hope could be solar powered.

Figure 7.7. The Siemens HQ in Munich, Germany. It consumes 90% less electricity and 75% less water than its predecessor, and has a platinum LEED certification, which is the highest level possible. Its sustainability features include solar cells on the roof that generate around a third of the required electricity, a system that collects rainwater for flushing toilets and watering the grounds, triple glazing angled such that the amount of natural light entering the building from the inner courtyards is maximised and artificial lighting use is therefore reduced, and the use of regionally-quarried natural stone tiles for parts of the exterior and flooring. (Courtesy of Siemens. www.siemens.com/press.)

It is becoming increasingly common for building companies to create sustainable buildings says Alex. ‘The demand is coming from multi-nationals who want buildings that are efficient and cheap to run, and who also want—as part of their corporate strategy—to show that they are lean and green,’ he explains, adding that there is evidence showing green credentials, such as having LEED accreditation for the headquarters, helps companies to be more successful.

‘There has been a fierce debate for 20 or 30 years in the academic literature about whether being green pays. But in the last 5 to 10 years, the argument is moving towards saying that there is empirical evidence that being a greener company will increase your sales markedly, and makes good economic sense. There are examples [of successful adoption of sustainability] at all scales large and small in every industry.’

‘Sustainability makes sense as it reduces costs,’ continues Alex, before admitting that there is not such a clear case for individual consumers looking to make their homes more sustainable. Working out the exact ‘payback time’—in other words how long it will take to make back the cost in fuel savings of the initial investment in sustainable technologies and features—is not particularly simple for individuals, he says.

‘The payback time will depend on how much you are saving on the energy you are producing. The main problem that we would face as individual homeowners is the payback times for these expensive technologies can be 10 to 20 years,’ explains Alex. This, he adds can make homeowners nervous of adopting sustainable technologies.

However he says that economic incentive schemes run by governments, such as feed-in tariffs that provide money for electricity generated and supplied to the national grid from domestic solar panels, can increase adoption of sustainable technologies. ‘Feed-in tariffs were spearheaded in Germany, and they have the most installed domestic solar panels anywhere in the world because of it,’ says Alex. (Box 7.3 describes a 2016 Belgian study on the economic viability of domestic solar panels used in conjunction with battery storage.)

Adoption of sustainable technologies is also a challenge for small businesses. ‘One of the big issues that people in my field are working on at the moment is corporate social responsibility for SMEs,’ says Alex, explaining that around 99% of the world’s companies are SMEs (small to medium enterprises with less than 250 employees) and very few currently operate sustainably. This, he says, has led a lot of sustainability experts to work with SMEs to try to increase their levels of corporate social responsibility.

‘SMEs face very different challenges to multi-nationals. They don’t have the same resources, and they don’t necessarily have the skills to change in order to become more sustainable. In the UK there are currently business groups and charities setting up networks that buddy up small companies with large multi-nationals. The skills from multi-nationals can then be passed down to smaller companies who want to be responsible businesses and are making efforts to become more environmentally sustainable. So for instance you might get the finance director from a big bank going and working for a few weeks in a small SME or even a charity or third sector organisation to help them and bring their knowledge down,’ explains Alex.

Box 7.3. The cost of creating your own electricity

When researchers Guilherme de Oliveira e Silva and Patrick Hendrick, from the Université Libre de Bruxelles in Belgium, analysed the cost for homeowners of becoming predominantly self-sufficient for electricity by generating their own from solar panels coupled to batteries they found it was not economically viable for most households. Their results show that homeowners could generate up to 40% of their own electricity from solar panels for a comparable price to buying electricity from the grid. But as soon as a greater percentage of self-sufficiency is attempted, energy storage needs to be installed so that solar energy can be stored for later use and the associated capital and installation cost greatly increases the cost of electricity compared with that from the grid. These results, published in 2016 in the journal *Applied Energy*, are based on Belgian data from the Royal Meteorological Institute and data from energy suppliers and solar panel installers that has been fed through a computer simulation.

‘It seems so simple and yet finding a home that produces its own electricity is so difficult,’ says Guilherme, a research engineer. He decided to find out why this was to help not only solar power designers and installers, but also to contribute useful data that can inform government policy decisions.

The type of installation Guilherme and Patrick modelled is shown in figure 7.8. It consists of a photovoltaic (solar panel) array and a lead-acid battery storage system that are both connected to the household’s domestic electricity main. The amount of electricity required by the house is known as the load. In a house with such a system installed the electricity flow throughout a day would follow the pattern shown in figure 7.9(a). As this diagram shows, the solar panels, not surprisingly, generate the most electricity in the middle part of the day and at those times provide the electricity supply for domestic use. Any excess energy generated is stored in the batteries, and when they reach their capacity is exported out to the grid. As the solar panel output falls later in the day, the household electricity needs are met from the batteries and finally the grid once the Sun is in and the batteries are discharged. (See figure 7.9(b)).

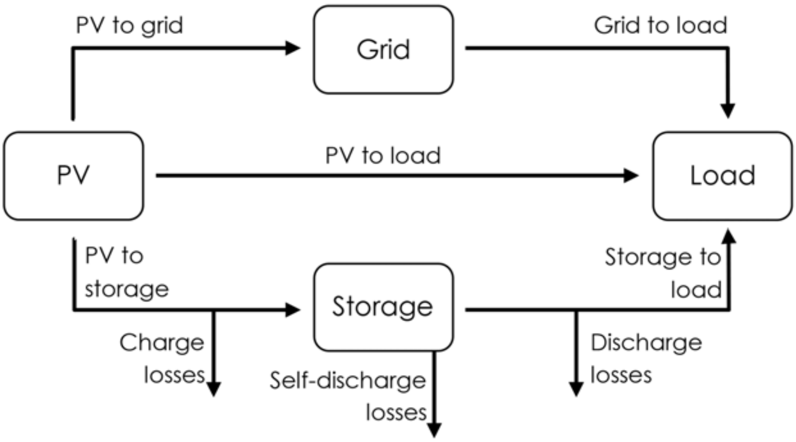

Figure 7.8. Schematic diagram of the type of installation modelled by Guilherme and Patrick. (Reprinted from Applied Energy, Vol 178, Guilherme de Oliveira e Silva, Patrick Hendrick, Lead-acid batteries coupled with photovoltaics for increased electricity self-sufficiency in households, Page 856–867, © (2016) with permission from Elsevier.)

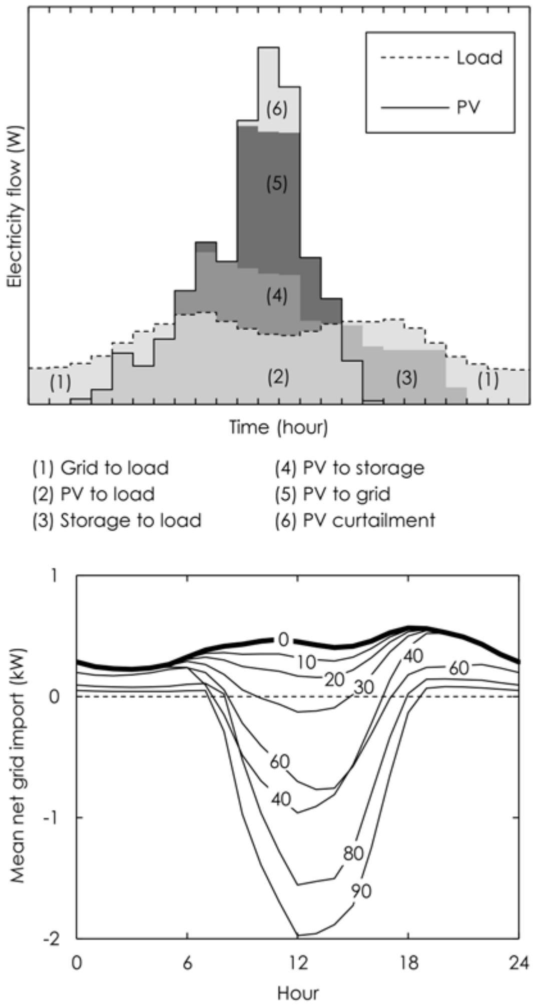

Figure 7.9. (a) The electricity flow throughout a day in a house with a system like that shown in figure 7.8 installed. (b) the mean net import of electricity from the grid with growing percentages of self-sufficiency. (Reprinted from Applied Energy, Vol 178, Guilherme de Oliveira e Silva, Patrick Hendrick, Lead-acid batteries coupled with photovoltaics for increased electricity self-sufficiency in households, Page 856–867, © (2016) with permission from Elsevier.)

One of the main disadvantages of solar power is that most households consume the majority of their electricity in the morning and evening when solar power is not available. In addition, domestic solar panel systems may place a greater strain on the power grid as the exporting of solar-generated electricity to the grid requires it to handle a higher amount of peak power, say the researchers. This ability needs to be built into the grid infrastructure, which is expensive.

‘The cost of electricity from the grid is the result of several components such as the generation of the electricity itself, its transport and distribution, and taxes. The transport and distribution cost components are strongly related to the grid infrastructure that must be built and maintained. As the cost of such infrastructure is strongly related to its power capacity, this ends up being reflected in the cost of electricity from the grid. So, in practice, the user will end up paying for the grid power capacity, even if not used to its full potential,' says Guilherme.

If more people install domestic solar panels, power plants will also need to respond more quickly to sudden changes in electricity demand. All these factors, say the researchers, combined with a decrease in the amount of electrical energy from the grid being consumed, would be likely to push up electricity prices.

However, looking to the future, Guilherme and Patrick think that if homeowners adopted a hybrid approach to sustainable energy use, by using several different types of energy source, this would make self-sufficiency financially viable. They also point out that the cost of batteries that can store energy for later use is dropping and that intelligent home electrical appliances are being developed that can spread out demand on the electricity supply.

'Solar power is, as is all distributed generation, a very disruptive force in the traditional power industry. But we often forget that the main goal today is to provide electricity reliably while fighting climate change, not to increase the amount of PV [photovoltaics] installed per se. PV, in both residential and commercial buildings, will probably play an important role in reaching that goal,' says Guilherme, adding that cost [which can be mitigated by support policies] is nevertheless an extremely important factor in determining uptake of solar power.

'The use of batteries coupled with PV will flourish only when it will become an economically viable option for the user as is happening in Germany where state incentives coupled with high grid electricity prices are leading to the widespread adoption of such systems,' says Guilherme.

Regulations are also driving uptake of sustainability in businesses, and their supply chains, Alex says. 'In the UK and US there are ISO (International Standards Office) standards for everything from quality, to health and safety. One of the standards is ISO14001, which is an environmental management standard, while ISO26000 is an international standard on corporate social responsibility. These standards help organisations to demonstrate that they are taking measures around social responsibility or environmental issues. A lot of the big companies have these because they can use them as a badge to say that they are doing it. The standards have clauses built into them which say that if you're working with suppliers, they should also have, or be working towards, these standards. So you're starting to push down with environmental standards, because a lot of SMEs supply large companies and to work with the big boys you have to have this,' says Alex, adding that the onus falls on the larger company to help their suppliers become more sustainable.

Looking at the global picture, he says there are good economic reasons why it is mainly northern European countries—and the companies based there—who have so far embraced sustainability. 'Denmark and Sweden don't have oil or gas. All they have is hydro and wind because that's the resource their country provides them. So in some ways they've had to become more energy efficient because of the resources they rely on. The UK has the best wind and wave resource in Europe. However we also have some of the best coal and gas in Europe, and in the 1970s and 1980s it was a lot cheaper to rely on that than to develop renewables,' says Alex, explaining that this has made the UK's take up of renewable technologies slower than in Germany, the Netherlands, and Scandinavian countries.

Similarly in the US, Alex says, the take up of sustainability tends to be state by state and driven by specific issues. 'In California for example they've had bad air pollution in their cities and trouble with water resources, and so they've had to take a much greener approach than some other states.'

'The big debate [among sustainability experts] in the UK at the moment is about our energy mix. A lot of people are saying that we need to have small scale decentralised energy generation at the building level or community level. But nobody really seems to know how we can make that happen. The technologies such as solar and wind exist. The question is more: how can we start using the technologies that do exist, and how can we bring new technologies to the market in a way that we can afford them,' says Alex, who feels that physics research towards reducing the cost of solar cells is particularly important for future uptake of sustainable energy systems. 'The problem with solar is the expense of silicon. Researchers are trying to come up with other materials that mimic what silicon does but are a lot cheaper, can be produced on a large scale, and are much more efficient,' he explains.

Alex is also seeing more business training becoming available for STEM university graduates which, he says, can help bring physics-based sustainable technologies to the end user faster. 'If you teach entrepreneurial skills to physicists, technologists, and engineers, rather than going and working in big multi-nationals graduates can spin out their own small companies. This would start taking some of these technologies to market in a different way. In the past graduates would go and work for a big company and be in their lab and working on their technologies which they may go on to commercialise. That's actually quite a slow route to market. Some students are coming up with fantastic technology designs, and new ways of working, so now the thinking is: could they then start their own business around that? We're seeing the rise of crowd funding raising money quite quickly, and this can get technologies into the hands of people much more quickly than going through the traditional route of R&D in large companies.'

'In the business school [at Northumbria University] we are now buddying up with the science school and the engineering school to put students together. So the designers are coming up with products, the engineers are making those products function, and the business students are looking at the ways they can get that to market,' says Alex. 'Five years ago you wouldn't have thought to teach physicists business skills, but now there are a lot of people creating start-ups and going self-employed, and this is already starting to change the market place.'

7.3 Visionary architecture

While real-life architecture must fulfil its purpose, and is limited by building techniques and the materials available, the boundaries of architectural thinking are set only by our imaginations. Visionary architects, like Neil Spiller, Hawskmoor Chair of Architecture and Landscape at the University of Greenwich London, seek to redefine our relationship with the buildings we live and work in. He works from an assumption that everything is possible and asks where that takes architecture. Physics-based technologies can influence visionary architecture and Neil—who considers himself a 'thought experimenter' and draws inspiration from a wide variety of subjects and genres ranging from surrealism to biotechnology (see figure 7.10)—says one of the latest technologies having an effect is augmented reality. In some of his latest work he is exploring how augmented reality could change our living and working spaces. (See box 7.4 for more on augmented reality.)

This could take the form, he explains, of virtual features overlaid over reality viewed through augmented reality glasses or a tablet. 'It is about how the real world

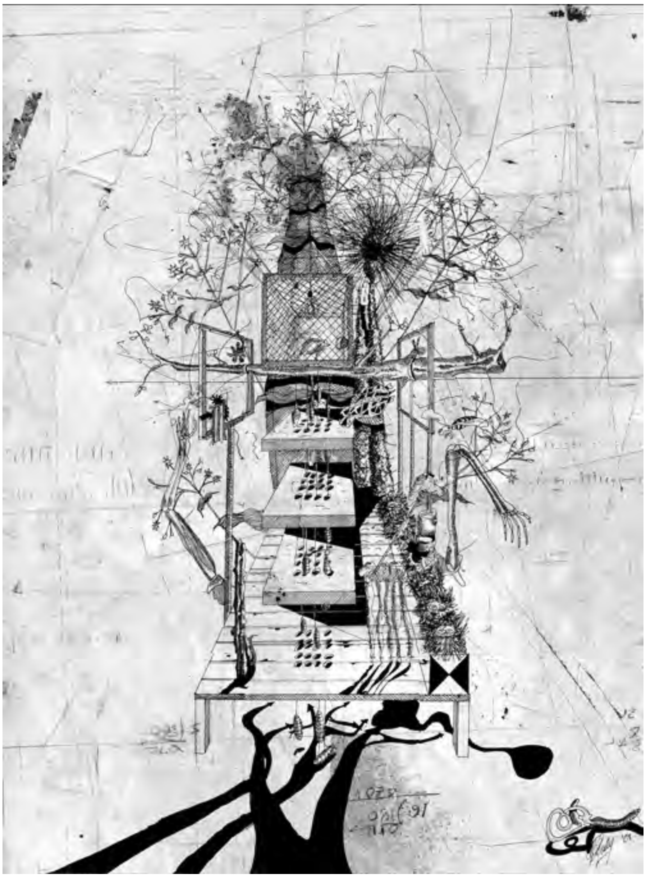

Figure 7.10. *Interior of the Chicken Computer* by Neil Spiller, 2009. This design references technology, art practice, and ideas from the surrealist artist Max Ernst. A pigeon sits in the chicken-wire box at the top and it pecks control objects on pulleys that drop through the multi-level stage and represent depictions of the human body in art and literature. This mechanism was inspired by a real-life United States military research programme to develop a missile system guided by the pecks of pigeons during the Second World War. Project Pigeon (later renamed Project Orcon for 'organic control') was led by the American behavioural scientist B F Skinner (1904–90), and successfully trained pigeons to peck at a moving image of a ship. (© Neil Spiller. Reproduced with permission.)

Box 7.4. Augmented reality

Augmented reality (AR) involves content, such as an image or text, being laid over our view of the real world. AR is viewed through a screen (often a tablet or smartphone screen) and has been used for various applications including marketing materials that enable 3D views of products to be seen, providing additional content in museums, and mobile gaming.

There are two main ways of creating AR—marker-based and markerless. Marker based systems use a real, physical object to tell the AR software where to overlay the virtual content. For example, a printed symbol on a piece of paper can be used as a marker. To see the AR content we need to view the marker either through the screen of a mobile device, or via a computer screen when the marker is positioned in front of a webcam. The AR software generates the virtual content on screen relative to the position and orientation of the marker. So as we look at our screens we see the virtual object or text appear as if it existed in real-world space.

Instead of using a marker, markerless AR systems use other information, such as GPS data and information on which way a mobile device is facing, to work out where and what AR content to display. For instance, an AR app for exploring a city centre would compare the location data from the mobile device with a database that tells it what virtual content to generate on the screen at that particular location.

cossets a series of virtual spaces. These are simple things that happen already. For example you can go into some art galleries, hold your iPad up to a picture and you'll see the history and provenance of the picture, the other pictures it is related to and how it fits into art history. These are things that are going to happen soon, or are starting to happen now, and they are catalysts for architectural thoughts,' says Neil, who is exploring where the boundaries of a house would be if you used augmented reality technology.

'Since 1998 I've worked on a surrealist drawing project called *Communicating Vessels*. The current component of that is called the Longhouse, and it comprises about 150 drawings. The narrative is that there is a surrealist history professor that develops a mad garden. Up until now you've never quite seen the house, but now I'm designing the house. It's not a house in a traditional sense. It's a series of objects that have three components to them: the actual built form of a house with its windows and all its contents, an augmented reality component, and a biotechnological, synthetic biology component. So every object has these three epistemologies, or personalities, that move over time,' he explains.

'If you imagine the house has a series of jutting out wings like bird's wings, they might on an actual house give you shelter like a veranda. But in the augmented version of the house those wings might beat for a short period of time, and the tips of those virtual wings might be able to sense their environment,' continues Neil. He says that running virtual sites over the actual sites of the building could potentially allow you to use your living space as a type of computer program, by generating a series of codes from the overlaid views of reality 'that might move the augmented version of the objects across the site and within and without the house. So you'd get these ghostly objects,' explains Neil, adding that his drawings of these ideas 'are fairly abstract and surreal.'

So far he has imagined these objects to be sculptures and ornaments in the garden, that are 'multi-scalar' and change and morph over time (see figure 7.11). 'So you get into all sorts of artistic ideas like the fragmentation of form, and it all fits into

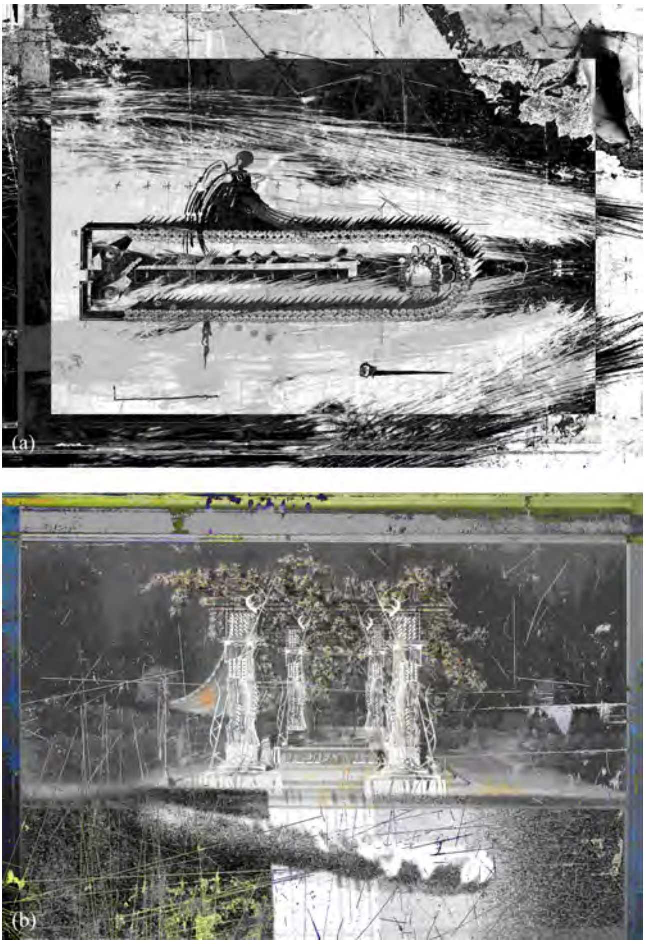

Figure 7.11. (a) *Skybadium Hippodrome Angel and Winged Clouds*, 2014, by Neil Spiller; (b) *Looking Toward Skybadium as Baguette Floats Past*, 2014, by Neil Spiller. Both these drawings are part of Neil's *Communicating Vessels* project. They show features of a virtual garden that would float over a memorial garden called the Walled Garden for Lebbeus, which was envisioned by Neil in remembrance of his friend, the American architect and artist Lebbeus Woods, who died in 2012 on the night Hurricane Sandy hit New York. In the corner of the garden there is a statue of Electra, who in Greek mythology is the bringer of storms. Anyone looking at the garden without any augmentation would simply see a walled memorial garden. But if they leaned into the hollowed back of Electra's head and looked through her eye holes they would see (and hear) an augmented reality storm, which represents the end of Lebbeus's life. The drawings aim to give a feel for the tumult of virtual rain and snow, as well as the progress of the storm as it rages then passes. (© Neil Spiller. Reproduced with permission.)

surrealist theory which [in terms of architecture] talks about things like metamorphosis, seeing familiar objects anew, and how you experience place and the materials around you. Surrealism isn't a thing of the past. We're living in a very surreal world. My duvet can blog, I can choreograph an augmented reality storm, or print a gun on my desktop. These are surreal technologies. So as architects we need to go back to surrealism and see if some of those tactics and protocols of space making might be useful in the contemporary world,' says Neil.

In addition to augmented reality Neil is also interested in the use of virtual reality to extend the boundaries of houses. He feels the increase from physical space into virtual space can benefit the occupants of buildings by giving 'an opportunity to personalise our spaces.'

'Architecture has become highly ubiquitous due to economic drivers, but because the virtual world is often cheaper there is the opportunity to use the envelopes that we're provided with in traditional architecture and embroider other spaces into them conditioned by our particular interests. So there's the opportunity of a much more personalised architecture for different people, which you can take with you [when you move out],' continues Neil, whose architectural designs have been exhibited around the world including in *Extreme Dreams*, a joint exhibition with sculptor Kris Kuksi at Cornell University in the United States in 2016.

Augmented reality could also provide useful new features, according to Neil. For instance, he imagines a future where you don't have to go out and buy a new cookbook, or download it to your tablet, as recipes could float virtually in mid-air summoned by hand gestures as you stand in your kitchen. 'I don't think it will be very long before we move towards these things,' he says.

While much of Neil's work only ever exists on paper or the screen, he occasionally designs real-life objects and structures. In 1994, when commissioned by a client to create a table, Neil found himself inspired by a then-emerging area of physics. 'In the early 1990s nanotechnology was a new thing just starting to be talked about, and I speculated about what this table might be if nanotechnology was a possibility,' he says. The result was *Hot Desk* (see figure 7.12).

'The gold and silver bits that you can see through the glass table top are modelled on the corpus callosum, which is the tube that joins both halves of the [human] brain together. On one level is it just a funny-shaped, pretty table. But intellectually it is a speculation about what happens if the computer desktop becomes something where you actually manipulate and touch objects and they dispense information when you touch them. So you arrange objects around your table and join them together and maybe they start to meld and join and you get new hybrid data,' explains Neil, who envisioned these objects as physically real but with the ability to metamorphose quite quickly [via nanotechnological processes] and act as receptacles for data.

Another area that interests Neil is so-called 'plectic' architecture which mixes the virtual world with reality. The term plectics, he explains, comes from the American theoretical physicist Murray Gell-Mann who defines plectics as the study of simplicity and complexity. Neil's work in this area considers architectural space as a type of seven-channel sound mixing desk.

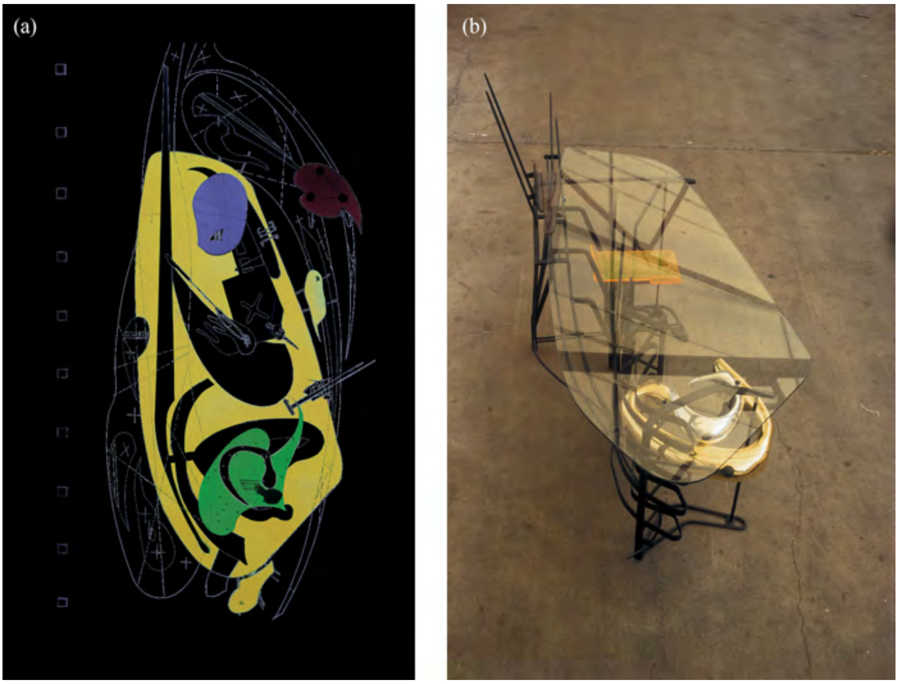

Figure 7.12. The 1994 collaborative project *Hot Desk*. (a) Initial drawing by Neil Spiller, illustrating his ideas for the *Hot Desk*. His ideas were then discussed with, and extrapolated from the drawing by, sixteen*(makers) in London who articulated Neil's vision in the actual desk (b). (Courtesy of Neil Spiller. Reproduced with permission.)

'There are elements of space, technology, narrative, semiotics, and performance, what I call cyborgian geography [a combination of real and virtual architecture that is influenced by local geography and technological enhancements to the human body], sensitivity, time, and scopic regimes—in other words how you look at architecture and how you define it. For example, you would look at a planet through a telescope, and might look at a carpet through a microscope. Architectural theory hasn't really worked around that because it has always been about anthropomorphic scale, the scale of our perception, and how we operate in the world. However there are an infinite number of spaces and scales beyond that which we can also manipulate for varying effect,' says Neil, who imagines a future where architecture is no longer limited by having to fit our bodies, or can only be viewed on the scale we see with our own eyes.

'Once you change the way in which we see and feel architecture, you change architecture itself,' he states. 'If our bodies had become different over millions of years our architecture would be different. Now we are at the stage where we are augmenting our bodies with prosthetics, virtual reality, augmented reality, synthetic biology, telescopes, and microscopes, and our architecture changes accordingly.'

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Weblinks

BREEAM
LEED
PassivHaus Trust
Sharc Energy Systems
Neil Spiller's personal website, which includes a gallery of drawings
You Tube video (silent film) of Project Orcon from the B. F. Skinner Foundation Video Archive
Video demonstrating Mercedes-Benz Accessories: Augmented Reality Apps
Augmented reality at Auckland Museum's marine exhibition: Moana -- My Ocean