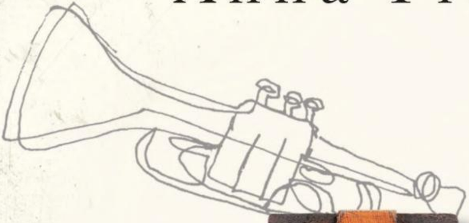
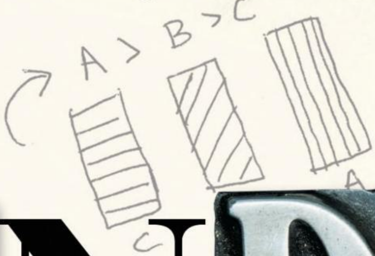
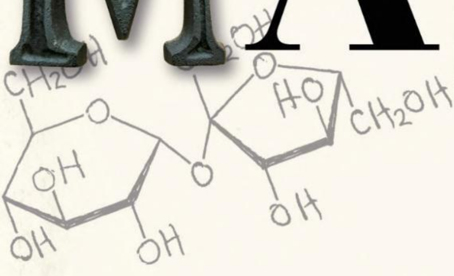
‘This book will make all your senses tingle.’
Roma Agrawal

Anna Ploszajski





HAND MADE



A scientist’s search for meaning through making

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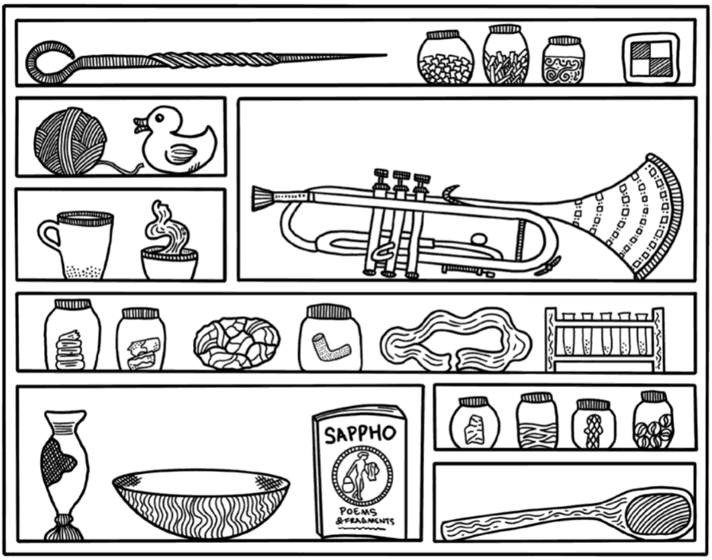


Prologue

As I descended the foam-lined staircase into the pub basement, the buzz of the bar became muffled into silence. Entering the underground venue, I saw rows of empty chairs and, following the eyeline of the imaginary seated crowd, my stomach lurched when my eyes fell upon the spot-lit microphone stand at the centre of the small, elevated wooden stage. I had a very bad feeling about this.

The audience gradually took their seats, and I sat in their midst, attempting a show of normality. As the event began, the MC introduced himself and I spilled beer down my chin. The folded print-out of my script grew damp between my sweating, shaking fingers, and I continually re-read it from the centre of the laughing crowd as the acts turned over, one by one, ticking down to me. I glanced over my shoulder towards the fire exit – it wasn't too late to feign illness. Or injury! Yes, an injury. Maybe I could stage some sort of terrible accident using this pint glass? Not enough to cause serious damage, obviously, but just enough so that –

My morose contemplation was interrupted when the MC suddenly shouted my name and the crowd clapped, whooped and cheered as directed. Mortified, I rose, shuffled along the cramped row of knees, and approached the empty platform. Grasping the microphone tightly, I moved its stand to the side of the stage. Its metal casing felt comfortingly cool beneath my flooded palm. Meanwhile, spotlights shone aggressively into my eyes, and my cheeks turned hot. The clamour subsided and was succeeded by silence. The front row gazed up at me, expectantly.

'Good evening everyone, my name's Anna,' I began, as rehearsed, startled to hear my amplified voice boom disembodied from the sound system, 'and I'm a materials scientist.'

*

Materials scientists study substances – metals, plastics, ceramics and glasses – by zooming in. The process starts at the human scale, which covers the objects we can hold and the surfaces we can feel, like the weighty microphone I was grasping in my tense hand that night, the coolness of the smooth metal shaft zapping nervous heat away from my skin.

Zooming in further, we reach the limits of human discernment by hands and eyes. These are the textures and constructions of materials, like the hard metal wire grille that pressed into my chin as I recited my opening jokes, and the soft plastic foam behind it whose bubbles flexed to cushion the shockwaves of air ejected from my lips as I spoke.

Material features smaller than this scale go beyond the limits of human perception. These are the microstructures that make up the invisible regions and arrangements of atoms inside materials. Like the familiar directionality of the grain in a piece of wood, the metal of the microphone casing is also made up of grains; areas of orderly stacked atoms bound together by physical forces to produce a collective, continuous substance.

Each of these grains – often far smaller than the eye can see – is made up of many millions of atoms. I usually think of them as spherical balls like marbles, crammed and jostling together, buzzing with the heat of the universe. Materials scientists zoom in all the way down here with instruments or imagination to see what these atoms are up to; how they arrange themselves next to each other, how they bond together with their neighbours, how they slip and slide over one another. These relationships dictate the very essence of a substance; strongly bonded atoms make rigid solids like metals and ceramics, atoms with weaker bonds between them are more likely to be found as soft plastics or liquids, and those with atoms which hardly notice each other at all will be happiest as a gas.

Sometimes it's necessary to zoom in even further than this, down to sub-atomic territory, to have a look at what atoms are made of – the protons and neutrons of the central nucleus, orbited by a troop of electrons. These basic atomic ingredients decide its element and position on the Periodic Table, from the smallest atoms – hydrogen – to the heaviest naturally occurring element, uranium. At this level, the laws of materials science break down, and quantum physics takes over. The very essence of matter becomes slippery and imprecise. In this dominion of the miniscule, atoms can't be thought of as balls at all but as mostly empty space; what were once solid particles are instead just flashes of light dancing in the darkness. I find it's usually best not to spend too much time thinking about what goes on down here.

Once we understand how materials are made by the different flavours and behaviours of atoms, and how they make up structures, textures and objects, we can then work out why materials are the way we find them. Why metals are heavy and conduct electricity, but plastics are light and don't. Or why glass is hard and strong but still susceptible to shattering catastrophically. Learn to read the language of atoms, and you'll unlock the mysteries of the material world.

The really exciting bit is that once we understand why materials are the way they are at all of these different length scales – from the micron to the microphone – we can then start modifying them to improve their properties for our own purposes, or dreaming up entirely new ones. Humans have been doing this for thousands of years, starting with blending different elemental ingredients of metal atoms together to make the alloy of bronze, and continuing in the materials science laboratories of today.

To my stunned surprise, my first stand-up comedy performance in that dingy pub basement was not a complete disaster. When the first wave of laughter washed over me it felt exhilarating, though I suspected that the audience were mostly just laughing to be kind. By the time I was wrapping up and passing the microphone back to the MC, relief became pure euphoria.

Growing up, nobody would ever have described me as the class clown. I had been roped into performing that night after taking an optional seminar in Public Engagement as a way of getting a break from the laboratory. The course leader had mistaken my eagerness to contribute to the session as extroversion; never one to let a teacher down, by the end of the day I had agreed to take part in a stand-up comedy night performed by researchers about their work. The trouble was, I was petrified of public speaking.

But something about stand-up intrigued me, and kept me coming back over the following months and years. At each gig my confidence grew, but my performance was never perfect. There was always a punchline that didn't land quite right, or a rhythm I couldn't catch. The same anecdotes could set one room on fire, but in another go down like an inexplicable lead balloon. The addictive counterbalance to this confusion was laughter, which felt far too good to walk away from, despite all the nerves. I became compelled to understand the chaotic relationship between audience and comic, and continued to chase the elusive perfect gig.

*

The more I publicly revealed myself as a materials scientist through comedy, the more questions my friends and audiences would ask. Why are phone screens made from glass, even though they always smash? Which is the best alternative to plastic? What do you call everything that isn't a material? The more they asked, the more cracks in my understanding of the material world were revealed. 'It's complicated,' I would shrug, 'that's an interesting question,' I'd stall, 'to be honest with you, I'm not really sure...'

I would spend my days in the laboratory mulling over this conundrum. It was deeply troubling that materials science couldn't find answers to these questions – or, more specifically, that *I* couldn't, even though I was supposedly the expert. Where could the answers lie?

One afternoon, I stood in my white lab coat frowning at a pressure gauge. The numbers on the ancient digital display should have been steadily creeping downwards as my pump evacuated the air inside the rigging of gas pipelines that I was using for my experiment. Instead, the figure was stoically stationary. This could only mean one thing: a leak. Sighing, I put the gurgling pump out of its misery, and introduced a small overpressure of air into the system, so that I could apply some washing-up liquid and watch for bubbling, like searching for a puncture underwater in a leaky bicycle innertube. The dribbling pipes started to fizz at the elbow-join culprit, where some copper piping must have come loose.

'That'll just take a quick solder to fix,' my supervisor advised. 'There's a new department just opened for stuff like this. It's called the Institute of Making. Why not go and see if they'll help you?'

So, clutching my broken pipe, I went off in search of this curious sounding place. Entering from the heaving throng of undergraduate students outside, I suddenly felt as if I had walked into an alternate universe. Floor-to-ceiling shelving displayed a plethora of up-lit objects: plump foamy sea sponges huddled next to creepy neon-green crystal bowls, and jaunty rubber ducks sat sentinel around a gleaming silver chalice. As my wide eyes climbed upwards, menacing barbed wire coiled high above my head, next to what appeared to be the bark of half a tree. On the opposite wall behind me, smaller shelves sported hundreds of sealed glass jars, each containing something different; an anonymous blue powder, white, crystalline sugar cubes, scrunched up purple plastic sheeting, a single pine cone. It was like an apothecary – not of medicine, but of materials.

'Can I help you?' asked a young, friendly-looking chap as I stood gawping at the display.

'Oh, er, yes please. I think I need to solder this copper joint back together,' I replied.

'Yep, that should be simple enough,' he said, turning it over in his hands. 'Want some help?'

Relieved at the offer, he led me through to the back of the space where a small workshop was set up. Tools glinted threateningly from their hooks on the walls. Some I recognised from my laboratory, but the purposes of many were a mystery. Several students appeared to be tinkering with curious constructions, stood around dusty metal benchtops clustered at the centre of the workshop. Intimidating mechanical saws and lathes crouched at the perimeter.

With the copper pipe gripped firmly by the jaws of a vice, my new instructor guided my unsteady hand as the blue blowtorch flame roared against the rosy metal. Touching the tip of the silver-coloured solder wire against the heated corner, it liquified instantaneously, and got sucked into the thirsty join. Capillary forces, I thought to myself. Nice.

'Great one!' the nice man enthused. 'That's a solid first solder. You should come and hang out here again. Maybe you might like to make something of your own from scratch next time?'

'Oh no, I – I couldn't. I don't …' I faltered, 'I wouldn't know where to start …'

The truth was that an ignominious childhood event had given me a lifetime aversion to anything related to hands-on making or arts and crafts. I was six years old at the time, and felt at the top of my game. That school year I'd made it onto the top maths table, and had accrued a record tally of gold stars. I was a high-flier and, to be honest with you, I knew it.

My class had been making cushions in our arts and crafts lesson, but mine hadn't quite gone as I'd hoped. It was supposed to be shaped like our new pet rabbit, Daisy, except its elongated face, fat and ill-defined ears and stocky, erect legs made it look more like a clawed anteater crossed with a pained camel than the cute bunny I had imagined. I stared at my cushion as it grinned maniacally out from amongst the display of lovely flowers and cupcakes which the other children had made, and felt my ears begin to burn with shame.

Suddenly, our teacher plucked my awful Frankensteinian creation from the pile and the whole class started clapping and turning to laugh at me.

'… special mention for the best effort!' I heard her say. After I sat back down, having collected my 'best effort' certificate (which might as well have been a wooden spoon, I thought), I hugged my grotesque bunny cushion to my chest and felt the tears begin to prick at my eyes.

Back in the workshop, once my newly fixed pipe was cool enough to carry away, I paused at the door, magnetically drawn back to this so-called Materials Library. Wandering over to the shelves, I strained to lift a weighty cannonball from where it was nestled in bristly astroturf, ran my hands over what I hoped was fake fur, heard the musical tinkling of plastic beads as they fell against their glassy jail. I cracked the lid of one jar only to be hit with an overpoweringly putrid pong and quickly tightened it back on. What was *that*? Come to think of it, what was any of this stuff?

As I explored, I felt a chasm opening in my understanding of materials. I knew the theories behind brittleness and elasticity, but I couldn't even begin to distinguish what materials most of these objects in front of me were even made out of. I had become so used to exploring the material world with a scientific probe that my own senses of perception had become thoroughly blunted.

It felt troubling, too, to experience some new and unfamiliar material properties embodied in these objects. Properties like disgust, pleasure, movement, amusement, rustle, allure, intrigue, menace. Rather than being inherent to the materials themselves, these traits seemed to be gifted from the objects they'd been made into.

What were these processes that could transform personalityless porcelain into a sophisticated teacup? Innocent steel into malevolent barbed wire? I certainly hadn't learnt about them in our Materials Processing lectures. As I finally made my way out through the exit, unhinged by this uncomfortable epiphany, my hand pushed against the glass of the door and I read the answer in backwards script printed on the other side:

Making

This book is the story of a naive scientist's exploration of materials as used in the handmade world. That first day at the Institute of Making, I learnt that materials science was just one storyline for this 'stuff,' and that there are all sorts of ways to understand materials without resorting to microscopes or calculators, such as history, design, anthropology and, yes, my dreaded 'arts and crafts.' Indeed, I hoped that these alternative narratives might help answer the questions about materials that my scientific knowledge alone could not account for.

Over the following months and years, I began to seek out artists, craftspeople and professionals who have dedicated their lives to materials. I took a research job at the Institute to continue my investigations, and the following chapters describe this journey.

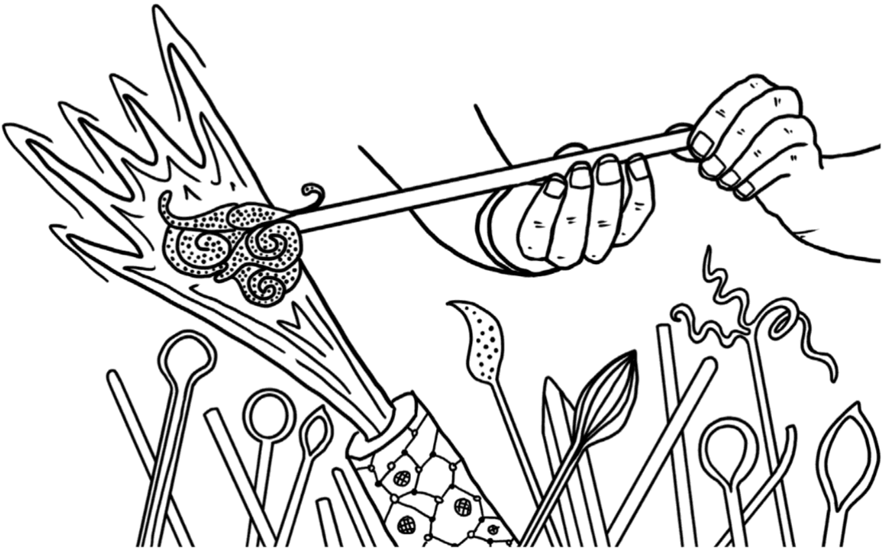
The ten materials featured in this book represent a diverse mixture of substances plucked from the detritus after my understanding of materials collapsed around me. Our story begins with glass, a well-studied material whose usage as laboratory test tubes, beakers, flasks and funnels makes it a familiar companion, and well within my scientific comfort zone. Sticking with substances recognisable from my scholarship, I explore plastic, steel, brass and clay, comprehensively covering the major materials categories of metals, plastics, ceramics and glasses.

There follows a leap into the unknown, with materials that had as yet gone unstudied, but that represent key players in the world of handmaking and craft. Sugar, a substance familiar at least to my palate, felt like a good place to start, although food as a class of materials was a novel idea. After this, I explore wool, wood, paper and stone; materials which fall into the loose category of 'natural materials,' those manufactured by animal, vegetable and mineral processes. All ten materials – be they staples from materials science or the world of craft – are presented here on an equal standing.

I realised on that first day in the Institute of Making that I would never truly grasp materials without literally getting my hands on them. So I waved farewell to my comfort zone to meet makers and try my hand at their crafts, in an attempt to paint the fullest picture of the materials in question. In addition to this, it wouldn't have been possible to profile the materials fully without looking into how they came to be, and I've done my best to provide as globally comprehensive a historical narrative as possible. Nevertheless, since my adventures were confined to the British Isles, the historical accounts have inevitably been centred on the making cultures and traditions of this region.

By searching for meaning through making, I began to make personal connections between the handmade material world and my own lived experiences. So, this book tells the story of a life intersected by those ten substances, which together reflect this overall journey of discovery. I hope that by the end, you'll be able to identify the tales told by materials in your own life, too.

Let's begin.



Glass

My phone alarm spooks me from fitful slumber, and for a moment I can't remember where I am. Groggily opening my eyes, I recall that my Dad had driven me here yesterday, and wouldn't be coming to get me for another three days. My heart sinks as I remember that this is the most important day of my life. And I've got the flu.

Sitting up, I swing my feet over the side of the single bed in the small, poky dormitory. Everything spins. My throat is swollen – too painful even to swallow – my nose thick with mucus, my eyes crusted over. I check the time. It's an hour and twenty-five minutes before my first Oxford entrance interview.

The wood-panelled office is exactly as I had imagined it, with worn, dark-green leather soft-furnishings and ancient peeling book spines stacked intimidatingly, mocking my naivety with the vastness of knowledge packed inside them. A professor sits behind a dark wooden desk – I've never met a professor before – and I apologise for having a bit of a cold before shaking her outstretched hand. A disgusted grimace paints her face.

The old wooden chair creaks as I sit down. I shift uncomfortably in my ill-fitting grey pin-striped trousers which I'd bought from the 'office' section of Bedford's New Look the previous Saturday. It's December and frosty outside; the atmosphere in the room is similarly chilly, but despite this I can tell that a betrayal of sweat patches is spreading through my thin mauve cardigan.

'So, [looks at paper on desk] Anna, I haven't read your application. Tell me about yourself and why you want to come and study Physics at Oxford.' I sense my face immediately expose my panic, and I mumble something about discovering how the universe works, but can't remember the authors of the popular science books I said I had read on my personal statement.

Pushing a piece of paper and a pencil towards me, the professor asks me a question, something to do with lightning strikes and cups of tea. My eyes begin to stream and I attempt to stem the flow with the dishevelled tissue I'm clutching in my clammy fist, cursing these pocketless smart clothes. I pick up the pencil and shakily draw the *x* and *y* axes of a graph, simultaneously blowing my nose whilst blindly feeling about through the fog in my brain for a lightbulb moment.

Similarly humiliating grillings ensue over the next two days. Sitting opposite a variety of physics professors, I blink a steady stream of tears out of my eyes, my face awash with the smears from fruitless attempts at applying make-up over my red raw skin. The illness is sucking all energy from my mind and body; I'm so exhausted that I'm just grateful to have a sit down in the interviews, after traipsing rain-soaked through the limestone quadrangles of this unfamiliar town in search of the right room. With each incomplete answer I feel my dream of studying physics here slowly slipping away. In between interviews, I sleep and dose up on medicine, counting down the hours to when I can leave.

The final morning dawns bright and crystal-clear, thin webs of ice having woven over the single-glazed windows overnight. My head feels clearer too, and the sickness seems to be passing, like the oppressive clouds that have now yielded to hopeful sunshine. I pack up my things and make my way over to the materials science building. This interview had come as a surprise free shot; the Department of Materials Science had written to say that they were low on applications that year, and so had invited physics applicants to interview with them, too. Without knowing anything about materials science, I thought I might as well take them up on their offer to increase my chances of getting in.

Around a table in a sunny conference room sit four professors of materials. The atmosphere is warm and informal; they know I hadn't originally applied for it, so they invite me to just chat with them about a broken hunk of metal plonked on the table between us. I feel relaxed and clear-headed. I croak my way through an easy mechanics question about a bouncy ball and leave feeling buoyed that I had done my best in at least one of the interviews, after the embarrassment of the previous three days.

A few weeks pass, and Christmas Eve dawns. From my bedroom I hear post flop onto the doormat in the hallway.

The stairs creak as Dad climbs to softly knock on my bedroom door. He hands me a thin beige envelope, then hastily retreats. This is it, the biggest crossroads of my eighteen years of life to date.

'Dear Miss Ploszajski,

We are delighted to offer you a place to study Materials Science at Mansfield College at the University of Oxford …'

A jolt of disappointment floods through me. Followed by gratitude. Followed by confusion. What exactly is materials science again?

Dad pokes his head around the door, 'Well?'

'I got in for materials science,' I reply, dumbstruck.

He pauses, 'Is … is that good?'

'Yeah,' I reply, 'I guess so. Looks like I'm going to Oxford!'

*

When I arrived, I worked hard, attending every lecture; even those which started early, my post-nightclub order of polystyrene-wrapped chips, cheese and beans lying still warm on my bedroom floor. I learnt about the chemistry of alloys, the engineering of composites, and the physics of light and how it interacts with materials like glass. It turns out that to understand glass requires an understanding of the equations that describe light as an electromagnetic wave, and the mathematics of quantum mechanics. Glass was the material that gave me the best of both worlds; a familiar backdoor labelled Physics through which I could explore the uncharted realm of Materials.

During my years as an undergraduate, my course-mates and I would spend afternoon practical sessions in the department's teaching labs, studying materials by testing them to breaking point and examining the remains through the glass eyepiece of a microscope. An unseen world of the fabric of 'stuff' would materialise: the grains of metals, which looked like a patchwork of fields viewed from an aeroplane; the Velcro-like tears of plastics ripped apart by force; the ripple-like fracturing of glass. Thanks to the light-bending abilities of glass lenses, theories and formulae were brought magically to life.

Glass remained my faithful friend into my engineering doctorate, a PhD-equivalent degree which I embarked upon after my undergraduate. The stuff was everywhere in my laboratory; glass beakers and funnels spilled out of cupboards, test tubes lay dirty in sinks, crusted with unknowable substances. In some experiments, special reinforced test tubes made from a thick layer of glass would insulate me from all sorts of invisible toxic gases, yet I could happily watch their effects on my materials as they changed colour or bubbled evilly, my nose just inches from the noxious fumes.

Alas, in the chaotic environment of a busy research laboratory, accidents are inevitable, and one day I smashed one of these special test tubes, fortunately without the deadly gas inside. People don't tend to cheer when you smash scientific glassware like they do with glasses in pubs, they just roll their eyes and tell you to go to the glassblower to get it fixed.[*]

Gingerly clutching my newly weaponised test tube, I sought out the glassblowers who resided in the chemistry department. As I knocked and entered, I couldn't believe the sight of this magical grotto. Glass was everywhere;

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[*] Come to think of it, a much higher proportion of my early research career was spent getting various pieces of equipment mended than I had initially anticipated.

bulbous pear-shapes tapered into delicate gossamer flutes, bubbly orbs nestled concentrically within sleek balloons, undulating transparent pipes zig-zagged snake-like inside oblong chambers. The roar of torches was accompanied by the clinking of stacked articles, finished and ready for collection by their lab-coated owners.

I'd never really considered the value of glassware until I broke a piece and saw it lovingly fixed by an artisan. As I peered over the glassblower's shoulder and watched him torch, turn and tempt the gooey glass back together, I wondered: what was so special about this stuff that the department employed two full-time glassblowers to make such custom equipment by hand? Why, when there's a whole catalogue of cheap plastics, sturdy metals and inert ceramics available, do we continue to clutch onto this easily breakable material? My scientific life owed this substance everything, and yet glass had evaded my attention until now.

Years later, when it came to seeking out my first craftsperson to speak to for this book, I didn't think twice before getting on my bike to meet specialists who straddle the craft and scientific world to handmake this crucial apparatus out of glass.

It's an unseasonably warm day in February, and I head east from home, past the restaurants and markets, mosques and motorways of London's East End until buzz gives way to suburbia. I'm early. Locking up my bike, a friendly black cat rubs against my legs, and leads me to a door, ajar, at the address I've been given. As soon as the cat slips inside, a large boot promptly appears through the opening – with yowling moggy attached – accompanied by a gruff 'Get lost, you b – '

'Um, hello?' I proffer, and, grateful not to be a cat, shake the welcoming hand of Terry, master glassblower at Chem Glassware, a family business that has been making

Silica molecules are SiO_2 – so they are made up of two oxygen atoms bonded to one silicon. In turn, these silica molecules bond together in three dimensions to form a chaotic, randomly arranged network. We describe this formation as 'amorphous.' The strong bonds in the silica network account for glass's high melting temperature, strength and hardness.

In the gaps between the network of silica molecules, but not actually part of the strongly-bonded structure itself, can sit other molecules, like soda (sodium oxide) and lime (calcium oxide) in soda lime glass, or lead atoms in lead glass. These additives change the properties of the glass, making the melt runnier, for example. The subtleties afforded to glass by these molecular modifiers are an important storyline in glass's history as a substance in the service of science.[*]

Glass has a long and rich lineage; the first archaeological examples from northern Syria, Mesopotamia and Egypt date back more than 5,000 years, though naturally-occurring glass, such as volcanic obsidian, was used as a sharp cutting tool by earlier Stone Age societies. The Ancient Egyptians developed glassmaking processes to make coloured ingots, beads and vessels by mixing and heating quartz sand and plant ash. These were not blown up into bubbles by the glass-worker's breath; early glass vessels were created by rolling a globule of molten glass around a removable solid clay core. Blowing glass into large, intricate forms came later, around the first century BC, popularised by the Romans.

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[*] We should remember at this point that we are dealing with structures of matter at extremely tiny scales; about a million silica molecules would fit side-by-side across the width of the full stop at the end of this sentence.

Prior to the formalisation of strictly scientific experimentation,[*] it was the alchemists of Europe, Africa, China and Asia who tinkered with matter in pursuit of miracle cures, elixirs of mortality and the transmutation of lead into gold. For almost two millennia, the predominant formulation of glass used by these experimentalists to contain their reactions was that of soda lime glass. Its transparency allowed for observation – an important part of the alchemic process – but it did, unfortunately, suffer from the material ailment of thermal shock.

This is the catastrophic cracking that occurs when a material expands too rapidly or too unevenly when heated; alchemical experiments would end up smashed across the benchtop when these tinkerers were too reckless with their flames. The invention of borosilicate glass – the stuff I would be working with alongside Charlie – by German glassmaker Otto Schott in the late 19th century changed everything. To find out how, it's time to take our first deep dive into the world of materials science, and zoom in to have a look at what the atoms are up to inside glass.

The secret to the special shock resistance of borosilicate glass is its molecular structure. It's a glass made from an amorphous web of silica and boron trioxide molecules; rather than incorporating different molecules in between

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[*] Science, as we think of it today – the systematic study of the universe using testable hypotheses and making mathematical approximations by observation – is a surprisingly modern concept. Up until the 19th century, the study of nature and the physical universe was called natural philosophy. Modern science branches into subjects such as chemistry, physics, biology, Earth- and space-sciences, whereas natural philosophy comprised topics such as the study of the cosmos, etiology (the study of causes), probability, infinity, nature, motion, space and time, and alchemy.

those in the silica network, the boron trioxide replaces some silicas to become part of the network itself.

To understand thermal shock, we must first understand heat. All atoms vibrate and buzz with the energy of the universe. Most of us think of temperature as equivalent to 'heat' – how we feel the warmth of the sun on our skin or the cold of an ice cube on our lips – but science can always be relied upon to un-romanticise such lovely experiences. To science, temperature is a manifestation of how much atoms in a material vibrate; hot atoms vibrate vigorously, and cold atoms vibrate less. The heat travels through a material because energy is transferred from these strongly vibrating atoms to their colder, more sedentry neighbours.

When materials get hotter, their atoms gain more energy, which causes them to vibrate more. This has the knock-on effect of making the bonds between the atoms longer. It explains why most materials expand when they get hot, because atoms that vibrate more energetically take up more space, like impassioned movers and shakers on the dancefloor. And if the atoms are taking up more space, then so too will the material object. But the genius of this kind of glass is that it doesn't expand very much at all when it gets hot. Why?

Two reasons. The first is that in the amorphous network structure of glass, the molecules are not packed together efficiently inside the material (unlike the regimented rows of atoms in ice and metals, which we'll meet later). This means that there are small gaps between the molecules in glass, which can accommodate the lengthening of the atomic bonds when the material is heated. The second reason is that the bonds in the network of silica and boron trioxide are particularly strong, so these bonds hold onto their atoms tightly and don't elongate as much as a weaker bond might when heated.

Old-fashioned soda lime glass didn't enjoy the benefits of such strong atomic bonds, and so, apparatus would expand unevenly when heated, and this would put the material under internal strain. If this strain became too much, then the material would crack. Without the handicap of thermal expansion, the invention of Schott's borosilicate glass allowed scientists to push this substance to its limits: making glass apparatus in ever more elaborate shapes, subjecting it to more extreme thermal conditions, and putting it to a diverse range of uses, from the humble test tube to advanced experimental set-ups. Thanks to its superior resistance to thermal shock, borosilicate glass has played a crucial supporting role in countless medical, scientific and technological discoveries from its invention to the present day.

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'To hand-work glass, we've got to wear these very fashionable didymium glasses,' says Charlie, handing me a pair of chunky plastic-rimmed spectacles. They look like sunglasses, but when I put them on the world becomes literally rose-tinted, and it takes a while to get used to. The lenses are made from the little-known elements praseodymium and neodymium. Didymium itself is a glass, and has the effect of blocking out yellowish light, dulling much of the glare from flames and red-hot glowing glass, which allows the glassworker to better see their work.

At the workstation, a torch is angled away from the seated glassblower and is controlled by two knobs. The first regulates the flow of gas, making the flame larger or smaller; the second controls the oxygen supply. The greater the oxygen supply, the hotter, fiercer and louder the flame. It reminds me of the Bunsen burners in my laboratory; increasing the oxygen generates the same blue, cone-shaped flame as opening the hole at the base of the Bunsen, except this flame is about five times as ferocious.

'Start with it fluffy,' Charlie demonstrates by delicately twisting the dials, 'and then add oxygen until it roars.'

She lightly clasps one end of a thin glass rod about a foot long, and places the other in the top of the roaring flame – the coolest part, furthest away from where she's sitting. 'You've got to keep it constantly twisting so that it's heated evenly on all sides,' she says, rolling the rod between her fingers and thumb. 'Even though this is borosilicate, it still needs to be heated up gradually. Then you can slowly bring it into the hotter part of the flame, and add oxygen to increase the heat.'

After about a minute of heating, the end of the glass rod begins to glow orange. It appears to get slightly chubbier, and the sharp edge created when Charlie snapped it off the longer rod becomes smooth. The globular end starts to droop, and as Charlie twists it in the flame, it continues to flip-flop due to the downward pull of gravity, the material steadily released from its rigidly solid form to become a deliciously viscous liquid.

There is another criterion for a material to be a glass, other than its amorphous molecular structure, which is that it exhibits a 'glass transition.' This is where a material is hard and brittle at low temperatures, but becomes a viscous, rubbery, treacle-like substance when heated. The glass transition isn't the same sort of material transformation as the melting of an ice cube at exactly 0°C. In ice, water molecules are arranged in a very precise and orderly configuration, called a crystal structure; a three-dimensional regiment of rows and columns made from evenly spaced molecules. Between the water molecules are weak bonds, which can be broken by heat. A temperature of 0°C is enough to break all

It's challenging to coordinate, and even more so when I introduce a second rod in my other hand. A concentrated silence descends.

When both rods are up to temperature, I collide them together, the orange glow briefly intensifying at the join. I bend the rods into a V-shape, and begin to twist them round each other, working my way up their lengths. 'That's it, you're getting it!', encourages Charlie.

I can picture what the graph of viscosity against temperature looks like for glass, but I've never actually felt the softening myself. It's amazing to sense this stiff, rigid material begin to yield under my hands. It softens the more I heat it, becomes tacky, and then silently vitrifies again as it cools out of the flame. All the changes must be felt by resistance; nothing visual shifts when the material changes state.

After a while, I've made a sort-of transparent glass scribble, and the two protruding straight rods I am holding are becoming distressingly short. 'Here you go,' says Charlie, handing me a third rod, this time thicker and green-coloured, and I begin the heating process again. I enjoy this new mixing of absence and presence of hue.

Glass is famously transparent – it was presumably this essential property that alchemists refused to compromise on in the early days, even if that meant it occasionally exploded from thermal shock. It's the principle property we celebrate in glass today; through it we bring light into our homes, observe the clarity of wine, and correct our vision by balancing it on our noses. The optics of glass are central to the microscopes and telescopes that widen our scientific horizons, in the study of both the very small and the very large. Glass is made to be looked through. But such an unremarkable, invisible property has a surprisingly complicated origin.

The amorphous network of molecules that make up glass is continuous throughout the structure. Glass doesn't have any regions where its molecules stack up into multitudes of crystals (as they do in metals), which means that a well-made piece of glass doesn't have any internal boundaries or other defects to scatter incoming light. Without those discontinuities in the structure, light can happily pass through glass, sailing between its disordered jumble of molecules unimpeded.

But this isn't quite the whole picture. In opaque materials, some light gets absorbed by the material's atoms. Light which isn't absorbed is reflected, bouncing off the object's atoms and into our eyes, giving us the visual impression of colour. White light is made up of the whole rainbow spectrum of colours. When some of these colours are absorbed by an object's atoms, we see the colours that aren't absorbed. For example, a tree's leaf absorbs red and blue light but reflects green, so it's green that we observe.

This isn't the case in colourless, transparent materials like glass, though. To understand the reason for this, we must take a deep breath and delve inside the atom itself.* You may remember from school that atoms are made up of a central nucleus containing protons and neutrons, with a number of electrons orbiting around it. The number of protons decides what element that atom is (and therefore the number of electrons, because these numbers usually balance); atoms of silicon and oxygen have 14 and 8 electrons respectively. But imagining atoms like this – a big central nucleus and electrons whizzing around nearby – is an appallingly inaccurate picture.

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* I know I said that I don't like to spend too much time thinking about the subatomic realm, but this is the one and only time we'll be venturing down here in this book. It'll be worth it, I promise.

The reality is that the vast majority of an atom is actually empty space. A popular analogy for this is a sports stadium; the pea-sized nucleus sits in the middle of the pitch, and the electrons are grains of sand in the outermost seats. But to introduce you to my world of materials, I'd like you to imagine yourself, instead, as a nucleus of an average-sized atom, floating halfway across the English Channel. At this scale, the 21-mile span of water between England and France represents the size of the atom, and you, my unfortunate friend, are the size of the nucleus. Your outermost electrons, each of which would be the size of a large cake, would be orbiting as far away from you as the shallows of Dover and Calais. Your other electrons are orbiting slightly closer by.

These electron-cakes are orbiting around you in different energy levels – imagine them floating on little rafts in the distinct rows of the shipping lanes.* At first, an electron-cake is assigned to a certain row of the shipping lane, but it could jump further away from you into a different row if it were given the energy. This energy could come from waves passing through the sea – in a real atom, it could come from waves of light passing through the material. However, the energy from the wave needs to be exactly the right amount to get the cake to surf into the next row of the shipping lane; not too strong but not too gentle. If it's not the right energy, the wave will simply pass by and the cake will bob around in its existing row, going nowhere. In other words, electrons need a precise injection of energy from incoming light in order to be promoted to a different energy level.

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* Shipping lanes are like multi-lane motorways for boats.

In the atoms of glass, the atomic energy levels are so far apart that no visible light has enough energy to surf the electrons into the next row. So, none of the light is absorbed, and all pass through the atom, rendering the material transparent.

There's a small catch.* Light waves aren't *totally* unaffected when they travel through glass. We know this because of the effect of triangular glass prisms that separate the sun's light into its rainbow constituents, and lenses that bend it in microscopes and eye glasses.

You may have heard of light described as an electromagnetic wave. These are oscillating electric and magnetic fields; forces of physics. These waves have nothing to do with matter or atoms; they can exist in vacuums (which is just as well, since that means the sun's light can reach us through the vacuum of space). In practice, what this means is that electromagnetic waves are affected by things that are electrically charged. Like electrons.

If you'll indulge my Channel analogy just one more time … when the waves pass by the cakes on rafts, although they don't have enough energy to move the cakes to another row of the shipping lanes, the cakes do still bob around when the wave passes. The same happens in the atom; electromagnetic waves of light that pass the electrons cause them to oscillate.

The motion of the cakes bobbing around causes them to produce their own ripples. These ripples meet and interfere with the big waves, slowing them down. In practice, this has the effect of causing light passing through glass to slow down relative to its travel through air, which contains

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* Sorry about that, welcome to science.

comparatively fewer electrons (gases being much less densely packed with atoms than solids). It's this phenomenon we have to thank for glass' ability to bend light when shaped like lenses – to magnify the microscopic universe of a petri dish, and bring into focus the macroscopic universe out there in space.

Here's the best bit. Have you ever noticed that when you look out of a window, you can also see a weak reflection of yourself superimposed on the view outside? These are the whispers of those oscillating electrons. The ripples from the oscillating cakes are given out in all directions, just like those concentric wavelets you'd see if you threw a pebble into a calm pond. This means that some ripples travel in the same direction as the big wave, but others travel in the opposite direction. It's the echo from the backwards-flowing ripples of oscillating electrons that we observe as a weak reflection when light passes through glass. (The polished flat surfaces of mirrors and glass window panes allow this light to escape and be detected by our eyes).

Phew. Thanks for joining me in the subatomic world, and congratulations for surviving. We've successfully used quantum mechanics to see why scientists throughout the ages valued glass so highly - its brilliant transparency. Now, back to the hayloft.

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Under Charlie's watchful eye, I become more confident with the glass, twisting and stretching it between the rods, fashioning it into a random tangle of glass curves and spirals. I didn't really have any sort of plan for it before I started; rather, I was led by the natural movements of the material under my hands. 'Maybe you could use it as a gin-and-tonic stirrer?', she suggests.

toughened piece of glass spread more easily than in normal glass, causing it to smash itself into thousands of blunt chunks. You may have seen the aftermath of this on street corners next to vandalised phone boxes or in the wreckage of a car crash.

However, scientific glassware is not made in this way. In fact, to be able to withstand the rigours of laboratory use, Ray shows me the importance of annealing glass to remove the internal strains in their finished pieces. They have a special polarised lens, through which it's possible to see the internal strain of glass in colourful ribbons and stripes. Before annealing, a recently made laboratory beaker shows a band of yellow around its rim, a clear sign, he tells me, of material under strain. After a number of hours in a heated chamber, the tension all but disappears. By understanding the needs of the molecules inside glass, Ray and Terry are able to meet the needs of their customers – strong, sturdy, reliable glassware.

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My final challenge from Charlie is glassblowing, an ancient technique whose rise in popularity is generally attributed to the Roman Empire, although it had been developed by craftspeople in Syria and the Middle East over the preceding centuries. Even then, glass wasn't a new material; other techniques for working and shaping glass into beads and simple shapes had been practised by many earlier cultures. Nevertheless, it was the Romans who made an industry out of the process of blowing down a pipe into a globule of molten glass, and inflating it into a vessel. If the glass was blown against the inside of a mould, shapely and intricate forms could be achieved; the Roman Empire became an epicentre for glass workshops.