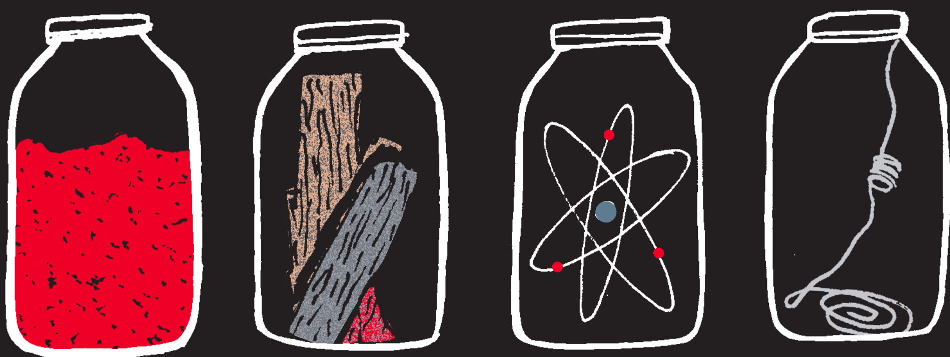
MARK MIODOWNIK

STUFF MATTERS



EXPLORING *the* MARVELOUS MATERIALS *that* SHAPE OUR MAN-MADE WORLD

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An eye-opening adventure deep inside the everyday materials that surround us, packed with surprising stories and fascinating science

WHY IS GLASS see-through? What makes elastic stretchy? Why does a paper clip bend? Why does any material look and b›ave the way it does? These are the sorts of questions that Mark Miodownik is constantly asking himself. A globally renowned materials scientist, Miodownik has spent his life exploring objects as ordinary as an envelope and as unexpected as concrete cloth, uncovering the fascinating secrets that hold together our physical world.

In *Stuff Matters,* Miodownik entertainingly examines the materials he encounters in a typical morning, from the steel in his razor and the graphite in his pencil to the foam in his sneakers and the concrete in a nearby skyscraper. He offers a compendium of the most astounding histories and marvelous scientific breakthroughs in the material world, including:

- the imprisoned alchemist who saved himself from execution by creating the first European porcelain
- the hidden gem of the Milky Way, a planet five times the size of Earth, made entirely of diamond
- graphene, the thinnest, strongest, stiffest material in existence—only a single atom thick—which could be used to make entire buildings sensitive to touch.

From the teacup to the jet engine, the silicon chip to the paper clip, the plastic in our appliances to the elastic in our underpants, our lives are overflowing with materials. Full of enthralling tales of the miracles of engineering that permeate our lives, *Stuff Matters* will make you see stuff in a whole new way.

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For Ruby, Lazlo, and Ida

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INTRODUCTION

AS I STOOD ON a train bleeding from what would later be classified as a thirteen-centimeter stab wound, I wondered what to do. It was May 1985, and I had just jumped on to a London Tube train as the door closed, shutting out my attacker, but not before he had slashed my back. The wound stung like a very bad paper cut, and I had no idea how serious it was, but being a schoolboy at the time, embarrassment overcame any sort of common sense. So instead of getting help, I decided the best thing would be to sit down and go home, and so, bizarrely, that is what I did.

To distract myself from the pain, and the uneasy feeling of blood trickling down my back, I tried to work out what had just happened. My assailant had approached me on the platform asking me for money. When I shook my head he got uncomfortably close, looked at me intently, and told me he had a knife. A few specks of spit from his mouth landed on my glasses as he said this. I followed his gaze down to the pocket of his blue anorak. I had a gut feeling that it was just his index finger that was creating the pointed bulge. Even if he did have a knife, it must be so small to fit in that pocket that there was no way it could do me much damage. I owned penknives myself and knew that such a knife would find it very hard to pierce the several layers that I was wearing: my leather jacket, of which I was very proud, my gray wool school blazer beneath it, my nylon V-neck sweater, my cotton white shirt with obligatory striped school tie half knotted, and cotton vest. A plan formed quickly in my head: keep him talking and then push past him on to the train as the doors were closing. I could see the train arriving and was sure he wouldn't have time to react.

Funnily enough I was right about one thing: he didn't have a knife. His weapon was a razor blade wrapped in tape. This tiny piece of steel, not much bigger than a postage stamp, had cut through five layers of my clothes, and then through the epidermis and dermis of my skin in one slash without any problem at all. When I saw that weapon in the police station later, I was mesmerized. I had seen razors before of course, but now I realized that I didn't know them at all. I had just started shaving at the time, and had only seen them encased in friendly orange plastic in the form of a Bic safety razor. As the police quizzed me about the weapon, the table between us wobbled and the razor blade sitting on it wobbled too. In doing so it glinted in the fluorescent lights, and I saw clearly that its steel edge was still perfect, unaffected by its afternoon's work.

Later I remember having to fill in a form, with my parents anxiously sitting next to me and wondering why I was hesitating. Perhaps I had forgotten my name and address? In truth I had started to fixate on the staple at the top of the first page. I was pretty sure this was made of steel too. This seemingly mundane piece of silvery metal had neatly and precisely punched its way through the paper. I examined the back of the staple. Its two ends were folded snugly against one another, holding the sheaf of papers together in a tight embrace. A jeweler could not have made a better job of it. (Later I found out that the first stapler was hand-made for King Louis XV of France with each staple inscribed with his insignia. Who would have thought that staplers have royal blood?) I declared it "exquisite" and pointed it out to my parents, who looked at each other in a worried way, thinking no doubt that I was having a nervous breakdown.

Which I suppose I was. Certainly something very odd was going on. It was the birth of my obsession with materials—starting with steel. I suddenly became ultra-sensitive to its being present everywhere. I saw it in the tip of the ballpoint pen I was using to fill out the police form; it jangled at me from my dad's key ring while he waited, fidgeting; later that day it sheltered and took me home, covering the outside of our car in a layer no thicker than a postcard. Strangely, I felt that our steel Mini, usually so noisy, was on its best behavior that day, materially apologizing for the stabbing incident. When we got home I sat down next to my dad at the kitchen table, and we ate my mum's soup together in silence. Then I paused, realizing I even had a piece of steel in my mouth. I consciously sucked the stainless steel spoon I had been eating my soup with, then took it out and studied its bright shiny appearance, so shiny that I could even see a distorted reflection of myself in it. "What is this stuff?" I said, waving the spoon at my dad. "And why doesn't it taste of anything?" I put it back in my mouth to check, and sucked it assiduously.

Then a million questions poured out. How is it that this one material does so much for us, and yet we hardly talk about it? It is an intimate character in our lives—we put it in our mouths, use it to get rid of unwanted hair, drive around in it—it is our most faithful friend, and yet we hardly know what makes it tick. Why does a razor blade cut while a paper clip bends? Why are metals shiny? Why, for that matter, is glass transparent? Why does everyone seem to hate concrete but love diamond? And why is it that chocolate tastes so good? Why does any material look and behave the way it does?

Since the stabbing incident, I have spent the vast majority of my time obsessing about materials. I've studied materials science at Oxford University, I've earned a PhD in jet engine alloys, and I've worked as a materials scientist and engineer in some of the most advanced laboratories around the world. Along the way, my fascination with materials has continued to grow—and with it my collection of extraordinary samples of them. These samples have now been incorporated into a vast library of materials built together with my friends and colleagues Zoe Laughlin and Martin Conreen. Some are impossibly exotic, such as a piece of NASA aerogel, which being 99.8 percent air resembles solid smoke; some are radioactive, such as the uranium glass I found at the back of an antique shop in Australia; some are small but stupidly heavy, such as ingots of the metal tungsten extracted painstakingly from the mineral wolframite; some are utterly familiar but have a hidden secret, such as a sample of self-healing concrete. Taken together, this library of more than a thousand materials represents the ingredients that built our world, from our homes, to our clothes, to our machines, to our art. The library is now located and maintained at the Institute of Making which is part of University College London. You could rebuild our civilization from the contents of this library, and destroy it too.

Yet there is a much bigger library of materials containing millions of materials, the biggest ever known, and it is growing at an exponential rate: the man-made world itself. Consider the photograph on page xiv. It pictures me drinking tea on the roof of my flat. It is unremarkable in most ways, except that when you look carefully it provides a catalog of the stuff from which our whole civilization is made. This stuff is important. Take away the concrete, the glass, the textiles, the metal, and the other materials from the scene, and I am left naked, shivering in midair. We may like to think of ourselves as civilized, but that civilization is in large part bestowed by material wealth. Without this stuff, we would quickly be confronted by the same basic struggle for survival that animals are faced with. To some extent, then, what allows us to behave as humans are our clothes, our homes, our cities, our stuff, which we animate through our customs and language. (This becomes clear if you ever visit a disaster zone.) The material world is not just a display of our technology and culture, it is part of us. We invented it, we made it, and in turn it makes us who we are.

The fundamental importance of materials to us is apparent from the names we have used to categorize the stages of civilization—the Stone Age, Bronze Age, and Iron Age—with each new era of human existence being brought about by a new material. Steel was the defining material of the Victorian era, allowing engineers to give full rein to their dreams of creating suspension bridges, railways, steam engines, and passenger liners. The great engineer Isambard Kingdom Brunel used it to transform the landscape and sowed the seeds of modernism. The twentieth century is often hailed as the Age of Silicon, after the breakthrough in materials science that ushered in the silicon chip and the information revolution. Yet this is to overlook the kaleidoscope of other new materials that also revolutionized modern living at that time. Architects took mass-produced sheet glass and combined it with structural steel to produce skyscrapers that invented a new type of city life. Product and fashion designers adopted plastics and transformed our homes and dress. Polymers were used to produce celluloid and ushered in the biggest change in visual culture for a thousand years: the cinema. The development of aluminum alloys and nickel superalloys enabled us to build jet engines and fly cheaply, thus accelerating the collision of cultures. Medical and dental ceramics allowed us to rebuild ourselves and redefine disability and aging—and, as the term *plastic surgery* implies, materials are often the key to new treatments used to repair our faculties (hip replacements) or enhance our features (silicone implants for breast enlargement). Gunther von Hagens's *Body Worlds* exhibitions also testify to the cultural influence of new biomaterials, inviting us to contemplate our physicality in both life and death.

This book is for those who want to decipher the material world we have constructed and find out where these materials came from, how they work, and what they say about us. The materials themselves are often surprisingly obscure, despite being all around us. On first inspection they rarely reveal their distinguishing features and often blend into the background of our lives. Most metals are shiny and gray; how many people can spot the difference between aluminum and steel? Woods are clearly different from

each other, but how many people can say why? Plastics are confusing; who knows the difference between polythene and polypropylene? I have chosen as my starting point and inspiration for the contents of this book the photo of me on my roof. I have picked ten materials found in that photo to tell the story of stuff. For each I try to uncover the desire that brought it into being, I decode the materials science behind it, I marvel at our technological prowess in being able to make it, but most of all I try to express why it matters.

Along the way, we find that, as with people, the real differences between materials are deep below the surface, a world that is shut off from most unless they have access to sophisticated scientific equipment. So to understand materiality, we must necessarily journey away from the human scale of experience into the inner space of materials. It is at this microscopic scale that we discover why some materials smell and others are odorless; why some materials can last for a thousand years and others become yellow and crumble in the sun; how it is that some glass can be bulletproof, while a wine glass shatters at the slightest provocation. The journey into this microscopic world reveals the science behind our food, our clothes, our gadgets, our jewelry, and of course our bodies.

But while the physical scale of this world is much smaller, we will find that its timescale is often dramatically bigger. Take, for example, a piece of thread, which exists at the same scale as hair. Thread is a man-made structure at the limit of our eyesight that has allowed us to make ropes, blankets, carpets, and, most importantly, clothes. Textiles are one of the earliest man-made materials. When we wear a pair of jeans, or any other piece of clothing, we are wearing a miniature woven structure, the design of which is much older than Stonehenge. Clothes have kept us warm and protected for all of recorded history, as well as keeping us fashionable. But they are high-tech too. In the twentieth century we learned how to make space suits from textiles strong enough to protect astronauts on the Moon; we made solid textiles for artificial limbs; and from a personal perspective, I am happy to note the development of stab-proof underwear woven from a synthetic high-strength fiber called Kevlar. This evolution of our materials technologies over thousands of years is something I return to again and again in this book.

Each new chapter presents not just a different material but a different way of looking at it — some take a primarily historical perspective, others a more personal one; some are conspicuously dramatic, others more coolly scientific; some emphasize a material's cultural life, others its astonishing technical abilities. All the chapters are a unique blend of these approaches, for the simple reason that materials and our relationships with them are too diverse for a single approach to suit them all. The field of materials science provides the most powerful and coherent framework for understanding them technically, but there is more to materials than the science. After all, everything is made from something, and those who make things — artists, designers, cooks, engineers, furniture makers, jewelers, surgeons, and so on — all have a different understanding of the practical, emotional, and sensual aspect of their materials. It is this diversity of material knowledge that I have tried to capture.

For instance, the chapter on paper is in the form of a series of snapshots not just because paper comes in many forms but because it is used by pretty much everyone in a myriad of different ways. The chapter on biomaterials, on the other hand, is a journey deep into the interstices of our material selves: our bodies, in fact. This is a terrain that is rapidly becoming the Wild West of materials science, where new materials are opening up a whole new area of bionics, allowing the body to be rebuilt with the help of bio-implants designed to mesh "intelligently" with our flesh and blood. Such materials have profound ramifications for society as they promise to change fundamentally our relationship with ourselves.

Because everything is ultimately built from atoms, we cannot avoid talking about the rules that govern them, which are described by the theory known as quantum mechanics. This means that, as we enter the atomic world of the small, we must abandon common sense utterly, and talk instead of wave functions and electron states. A growing number of materials are being designed from scratch at this scale, and can perform seemingly impossible tasks. Silicon chips designed using quantum mechanics have already brought about the information age. Solar cells designed in a similar way have the potential to solve our energy problems using only sunshine. But we are not there yet, and still rely on oil and coal. Why? In this book I try to shed some light on the limits of what we can hope to achieve by examining the great new hope in this arena: graphene.

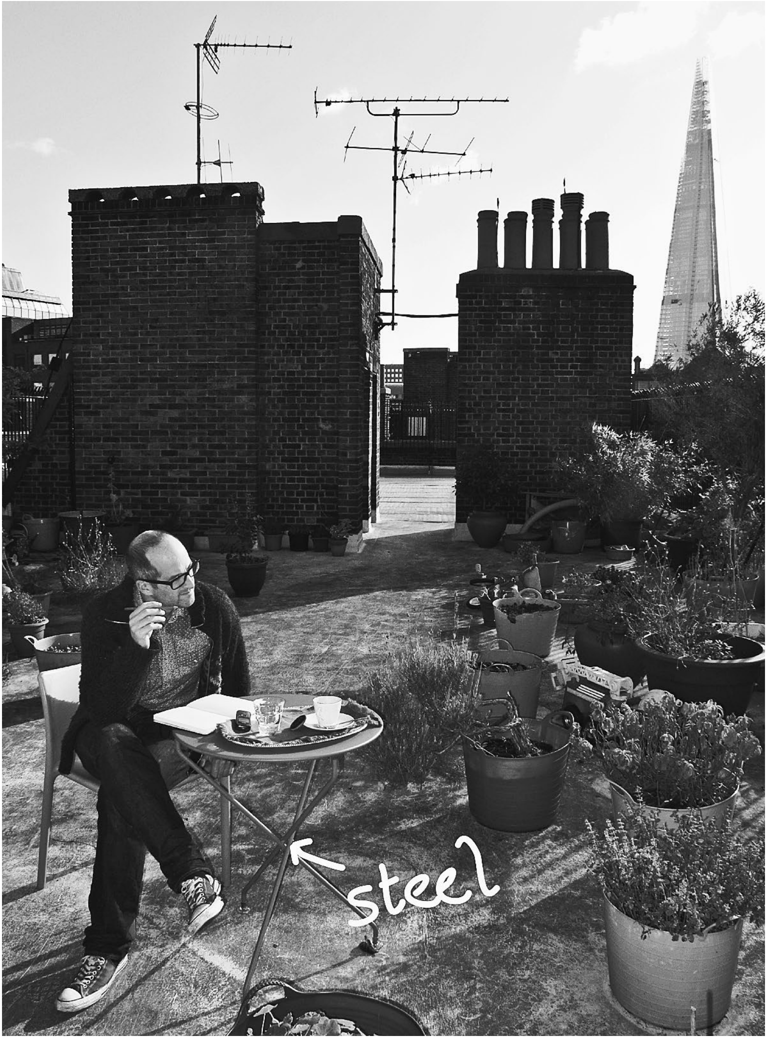
The central idea behind materials science is that changes at these invisibly small scales impact a material's behavior at the human scale. It is this process that our ancestors stumbled upon to make new materials such as bronze and steel, even though they did not have the microscopes to see what they were doing—an amazing achievement. When you hit a piece of metal you are not just changing its shape, you are changing the inner structure of the metal. If you hit it in a particular way, this inner structure changes in such a way that the metal gets harder. Our ancestors knew this from experience even though they didn't know why. This gradual accumulation of knowledge got us from the Stone Age to the twentieth century before any real appreciation of the structure of materials was understood. The importance of that empirical understanding of materials, encapsulated in such crafts as the blacksmith's, remains: we know almost all of the materials in this book with our hands as well as our heads.

This sensual and personal relationship with stuff has fascinating consequences. We love some materials despite their flaws, and loathe others even if they are more practical. Take ceramic. It is the material of dining: of our plates, bowls, and cups. No home or restaurant is complete without this material. We have been using it since we invented agriculture thousands of years ago, and yet ceramics are chronically prone to chip, crack, and shatter at the most inconvenient times. Why haven't we moved to tougher materials, such as plastic or metal for our plates and cups? Why have we stuck with ceramic despite its mechanical shortcomings? This type of question is studied by a vast variety of academics, including archaeologists and anthropologists, as well as designers and artists. But there is also a scientific discipline especially dedicated to systematically investigating our sensual interactions with materials. This discipline, called psychophysics, has made some very interesting discoveries. For instance, studies of "crispness" have shown that the sound created by certain foods is as important to our enjoyment of them as their taste. This has inspired some chefs to create dishes with added sound effects. Some potato chip manufacturers, meanwhile, have increased not just the crunchiness of their chips but the noisiness of the chip bag itself. I explore the psychophysical aspects of materials in a chapter on chocolate and show that it has been a major driver of innovation for centuries.

This book is by no means an exhaustive survey of materials and their relationship to human culture, but rather a snapshot of how they affect our lives, and how even the most innocuous of activities like drinking tea on a roof is founded on a deep material complexity. You don't have to go into a museum to wonder at how history and technology have affected human culture; their effects are all around you now. Most of the time we ignore them. We have to: we would be treated as lunatics if we spent the whole time running our fingers down a concrete wall and sighing. But there are times for such contemplation: being stabbed in a Tube station was one of them for me, and I hope this book provides another for you.

STUFF MATTERS

1 INDOMITABLE



I HAD NEVER BEEN asked to sign a non-disclosure agreement in the bathroom of a pub before, so it came as something of a relief to discover that this was all that Brian was asking me to do. I had met Brian for the first time only an hour earlier. We were in Sheehan's, a pub in Dun Laoghaire that wasn't far from where I worked at the time in Dublin. Brian was a red-faced man in his sixties with a walking stick for his bad leg. He was smartly dressed in a suit and had thinning gray hair with a yellowish tinge. He chain-smoked Silk Cut cigarettes. Once Brian found out that I was a scientist he guessed rightly that I would be interested to hear stories of his life in London in the 1970s, when he was in the right place at the right time to trade Intel 4004 silicon chips, which he imported in boxes of twelve thousand for £1 each and sold in small batches to the fledgling computer industry for £10 each. When I mentioned that I was researching metal alloys in the Mechanical Engineering Department of University College Dublin, he looked pensive and was quiet for the first time. I took this as an opportune moment to head to the bathroom.

The non-disclosure agreement was scrawled on a piece of paper which he had clearly just ripped out of his notebook. The contents were brief. They stated that he was going to explain his invention to me but I had to keep it confidential. In return he was to pay me one Irish pound. I asked him to tell me more, but he comically mimed the zipping of his lips. I wasn't quite sure why we had to have this conversation in a bathroom stall. Over his shoulder I saw other drinkers come in and out of the bathroom. I wondered if I should cry out for help. Brian searched in his jacket and got out a pen. A scruffy pound note emerged from his jeans. He was very insistent.

I signed the paper against the graffiti-daubed wall. He signed too, gave me the pound, and the slip of paper became a legal document.

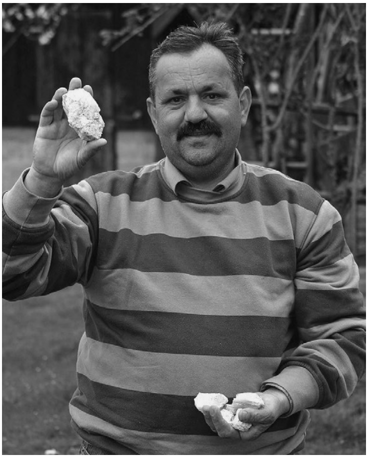
Back by the bar with our drinks, I listened as Brian explained that he had invented an electronic machine that sharpened blunt razor blades. This would revolutionize the shaving business, he explained, because people would need to own only one razor in their lives. At a stroke it would put the billion-dollar industry out of business, make him an exceptionally rich man, and reduce consumption of Earth's mineral wealth. "How about that?" he said, taking a triumphant gulp of his pint.

I eyed him with suspicion. Sooner or later every scientist has his ear bent by someone with a crackpot idea for an invention. In addition, razor blades were a sensitive subject for me. I felt prickly and uncomfortable as I became aware of the long scar down my back, the result of my encounter on the platform at Hammersmith station. But I gestured for him to continue and kept listening . . .

It is an odd fact that steel was not understood by science until the twentieth century. Before that, for thousands of years, the making of steel was handed down through the generations as a craft. Even in the nineteenth century, when we had an impressive theoretical understanding of astronomy, physics, and chemistry, the making of iron and steel on which our Industrial Revolution was based was achieved empirically—through intuitive guesswork, careful observation, and a huge slice of luck. (Could Brian have had such a slice of luck and simply stumbled upon a revolutionary new process for sharpening razor blades? I found that I wasn't prepared to dismiss the idea.)

During the Stone Age, metal was extremely rare and highly prized, since the only sources of it on the planet were copper and gold, which occur naturally, if infrequently, in the Earth's crust (unlike most metals, which have to be extracted from ores). Some iron existed too, most of it having fallen from the sky in the form of meteorites.

Radivoke Lajic, who lives in northern Bosnia, is a man who knows all about strange bits of metal falling from the sky. Between 2007 and 2008 his house was hit by no fewer than five meteorites, which is statistically so hugely unlikely that his claim that aliens were targeting him seems almost reasonable. Since Lajic went public with his suspicions in 2008, his house has been hit by another meteorite. The scientists investigating the strikes have confirmed that the rocks hitting his house are real meteorites and are studying the magnetic fields around his house to try to explain the extremely unusual frequency of them.

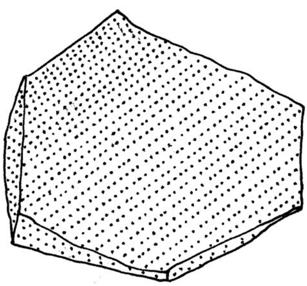


Radivoke Lajic and the five meteorites that have hit his house since 2007.

In the absence of copper, gold, and meteoric iron, our ancestors' tools during the Stone Age were made of flint, wood, and bone. Anyone who has ever tried to make anything with these kinds of tools knows how limiting they are: if you hit a piece of wood it either splinters, cracks, or snaps. The same is true of rock or bone. Metals are fundamentally different from these other materials because they can be hammered into shape: they flow, they are malleable. Not only that, they get stronger when you hit them; you can harden a blade just by hammering it. And you can reverse the process simply by putting metal in a fire and heating it up, which will cause it to get softer. The first people to discover these properties ten thousand years ago had found a material that was almost as hard as a rock but behaved like a plastic and was almost infinitely reusable. In other words, they had discovered the perfect material for tools, and in particular cutting tools like axes, chisels, and razors.

This ability of metals to transform from a soft to a hard material must have seemed like magic to our ancient ancestors. It was magic to Brian too, as I soon found out. He explained that he had invented his machine by trial and error, with no real appreciation of the physics and chemistry at play, and yet it seemed that he had somehow succeeded. What he wanted from me was to measure the sharpness of the razors before and after they had been through his process. Only this evidence would allow him to begin serious business discussions with the razor companies.

I explained to Brian that it would take more than a few meas-

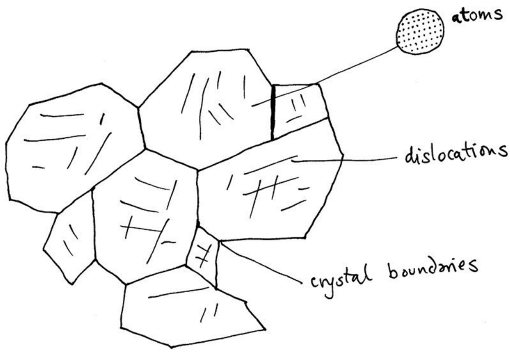


A metal crystal, such as exists inside a razor. The rows of dots represent atoms.

urements for them to take him seriously. The reason is that metals are made from crystals. The average razor blade contains billions of them, and in each of these crystals the atoms are arranged in a very particular way, a near-perfect three-dimensional pattern. The bonds between the atoms hold them in place and also give the crystals their strength. A razor gets blunt because the many collisions with hairs that it encounters force bits of these crystals to rearrange themselves into a different shape, making and breaking bonds and creating tiny dents in the smooth razor edge. Resharpening a razor through some electronic mechanism, as he proposed, would have to reverse this process. In other words, it would have to move atoms around to rebuild the structure that had been destroyed. To be taken seriously, Brian would need not just evidence of such rebuilding at the scale of the crystals but a plausible explanation at the atomic scale of the mechanism by which it worked. Heat, whether electrically produced or not, usually has a different effect than the one he was claiming: it softens metal crystals, I explained. Brian was adamant that his electronic machine wasn't heating the steel razors.

It may be odd to think that metals are made of crystals, because our typical image of a crystal is of a transparent and highly faceted gemstone such as a diamond or emerald. The crystalline nature of metals is hidden from us because metal crystals are opaque, and in most cases microscopically small. Viewed through an electron microscope, the crystals in a piece of metal look like crazy paving, and inside those crystals are squiggly lines—these are dislocations. They are defects in the metal crystals, and represent deviations in the otherwise perfect crystalline arrangement of the atoms—they are atomic disruptions that shouldn't be there. They sound bad, but they turn out to be very useful. Dislocations are what make metals so special as materials for tools, cutting edges, and ultimately the razor blade, because they allow the metal crystals to change shape.

You don't need to use a hammer to experience the power of dislocations. When you bend a paper clip, it is in fact the metal crystals that are bending. If they didn't bend, the paper clip would be brittle and snap like a stick. This plastic behavior is achieved by the dislocations moving within the crystal. As they move they transfer small bits of the material from one side of the crystal to the other. They do this at the speed of sound. As you bend a paper



I have only shown a few dislocations in this sketch to make them easy to see. Normal metals have enormous numbers of dislocations which overlap and intersect.

clip, you are causing approximately 100,000,000,000,000 dislocations to move at a speed of thousands of hundreds of meters per second. Although each one only moves a tiny piece of the crystal (one atomic plane in fact), there are enough of them to allow the crystals to behave like a super-strong plastic rather than a brittle rock.

The melting point of a metal is an indicator of how tightly the metal atoms are stuck together and so also affects how easily the dislocations move. Lead has a low melting point and so dislocations move with consummate ease, making it a very soft metal. Copper has a higher melting point and is stronger. Heating metals allows dislocations to move about and reorganize themselves, with one of the outcomes being that it makes metals softer.

Discovering metals was an important moment in pre-history, but it didn't solve the fundamental problem that there wasn't very much metal around. One option, clearly, was to wait for some more to drop from the sky, but this requires a huge amount of patience (a few kilograms fall to the surface of the Earth every year, but mostly into the oceans). At some point humans made the discovery that would end the Stone Age and open the door to a seemingly unlimited supply of the stuff. They discovered that a certain greenish rock, when put into a very hot fire and surrounded by red-hot embers, turns into a shiny piece of metal. This greenish rock was malachite, and the metal was, of course, copper. It must have been the most dazzling revelation. Suddenly the discoverers were surrounded not by dead inert rock but by mysterious stuff that had an inner life.

They would have been capable of performing this transformation with only a few particular types of rock, such as malachite, because getting it to work reliably depends not just on identifying these rocks but also on carefully controlling the chemical conditions of the fire. But they must have suspected that those rocks that didn't work, that remained obstinately rock-like however hot the fire became, had hidden secrets. They were right. It's a process that works for many minerals, although it would be thousands of years before an understanding of the chemistry required (controlling the chemical reactions between the rock and the gases created in the fire) led to the next real breakthrough in smelting.

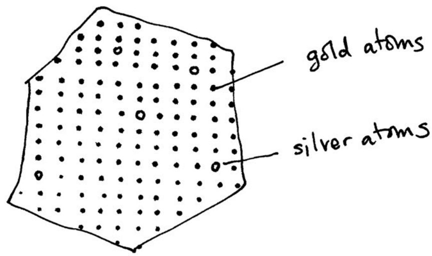
In the meantime, from around 5000 BC, early metalsmiths used trial and error to hone the process of the production of copper. The making of copper tools initiated a spectacular growth in human technology, being instrumental in the birth of other technologies, cities, and the first great civilizations. The pyramids of Egypt are an example of what became possible once there were plentiful copper tools. Each block of stone in each pyramid was extracted from a mine and individually hand-carved using copper chisels. It is estimated that ten thousand tons of copper ore were mined throughout ancient Egypt to create the three hundred thousand chisels needed. It was an enormous achievement, without which the pyramids could not have been built, however many slaves were used, since it is not practical to carve rock without metal tools. It is all the more impressive given that copper is not the ideal material for cutting rock since it is not very hard. Sculpting a piece of limestone with a copper chisel quickly blunts the chisel. It is estimated that the copper chisels would have needed to be sharpened every few hammer blows in order for them to be useful. Copper is not ideal for razor blades for the same reason.

Gold is another relatively soft metal, so much so that rings are very rarely made from pure gold metal because they quickly scratch. But if you alloy gold, by adding a small percentage of other metals such as silver or copper, you not only change the color of the gold—silver making the gold whiter, and copper making the gold redder—you make the gold harder, much harder. This changing of the properties of metals by very small additions of other ingredients is what makes the study of metals so fascinating. In the case of gold alloys, you might wonder where the silver atoms go. The answer is that they sit inside the gold crystal structure, taking the place of a gold atom, and it is this atom substitution inside the crystal lattice of the gold that makes it stronger.

Alloys tend to be stronger than pure metals for one very simple reason: the alloy atoms have a different size and chemistry from the host metal's atoms, so when they sit inside the host crystal they cause all sorts of mechanical and electrical disturbances that add up to one crucial thing: they make it more difficult for dislocations to move. And if dislocations find it difficult to move, then the metal is stronger, since it's harder for the metal crystals to change shape. Alloy design is thus the art of preventing the movement of dislocations.

These atom substitutions happen naturally inside other crystals too. A crystal of aluminum oxide is colorless if pure but becomes blue when it contains impurities of iron atoms: it is the gemstone called sapphire. Exactly the same aluminum oxide crystal containing impurities of chromium is the gem called ruby.

The ages of civilization, from the Copper Age to the Bronze Age



Gold alloyed with silver at the atomic scale, showing how the silver atoms replace some of the gold atoms in the crystal.

to the Iron Age, represent a succession of stronger and stronger alloys. Copper is a weak metal, but naturally occurring and easy to smelt. Bronze is an alloy of copper, containing small amounts of tin or sometimes arsenic, and is much stronger than copper. So, if you had copper and you knew what you were doing, for very little extra effort you could create weapons and razors ten times stronger and harder than copper. The only problem is that tin and arsenic are extremely rare. Elaborate trade routes evolved in the Bronze Age to bring tin from places such as Cornwall and Afghanistan to the centers of civilization in the Middle East for precisely this reason.

Modern razors are also made from an alloy but, as I explained to Brian, it is a very special sort of alloy, the existence of which puzzled our ancestors for thousands of years. Steel, the alloy of iron and carbon, is even stronger than bronze, with ingredients that are much more plentiful: pretty much every bit of rock has some iron in it, and carbon is present in the fuel of any fire. Our ancestors didn't realize that steel was an alloy—that carbon, in the form of charcoal, was not just a fuel to be used for heating and reshaping iron but could also get inside the iron crystals in the process. Carbon doesn't do this to copper during smelting, nor to tin or bronze, but it does to iron. It must have been incredibly mysterious—and only now with a knowledge of quantum mechanics can we truly explain why it happens (the carbon in steel doesn't take the place of an iron atom in the crystal, but is able to squeeze in between the iron atoms, creating a stretched crystal).

There is another problem, too. If iron becomes alloyed with too much carbon—if, for instance, it contains 4 percent carbon instead of 1 percent carbon—then it becomes extremely brittle and essentially useless for tools and weapons. This is a major obstacle because inside a fire there is rather a lot of carbon around. Leave the iron in too long, or allow it to become liquid in the fire, and a huge amount of carbon enters the metal crystals, making the alloy very brittle. Swords made from this high-carbon steel snap in battle.

Until the twentieth century, when the alloying process was first fully explained, no one understood why some steelmaking processes worked and others didn't. They were established by trial and error, and those that were successful were handed down to the next generation and were often trade secrets. But even if they were stolen, they were so complicated that the chances of successfully reproducing someone else's steelmaking process were very low. Certain metallurgical traditions in certain cultures became known for making extremely high-quality steel, and such civilizations thrived.

In 1961 Professor Richmond from Oxford University discovered a pit that had been dug by the Romans in AD 89. It contained 763,840 small two-inch nails, 85,128 medium nails, 25,088 large nails, and 1,344 extra-large sixteen-inch nails. The hoard was of iron and steel and not gold, which most people would have found bitterly disappointing. But not Professor Richmond. Why, he asked himself, would a Roman legion bury seven tons of iron and steel?

The legion had been occupying the advance headquarters of Agricola in a place called Inchtuthil in Scotland. This was at the outer reaches of the Roman Empire, and their mission was to protect its border from what they saw as the savage tribes who threatened it: the Celts. The legion of five thousand men occupied the region for six years before retreating and, in the process, abandoning their fort. They made great efforts to leave behind nothing that could help their enemies. They smashed all food and drink containers and burned the fort to the ground. But they weren't satisfied with this. In the ashes were the steel nails that had held the fort together, and they were far too valuable to be left to the tribes that had driven them out. Iron and steel were the materials that enabled the Romans to build aqueducts, ships, and swords; they allowed them to engineer an empire. Leaving the nails to their enemies would have been as useful as leaving a cache of weapons, so they buried them in a pit before marching south. As well as their weapons and armor, among the few, smaller steel objects that they probably did take with them were *novacili,* an object that epitomized their civilized approach to life: the Roman razor blade. These *novacili,* and the barbers who wielded them, allowed the Romans to retreat clean-shaven, groomed in order to distinguish themselves from the savage hordes that had driven them out.

The mystique that surrounded steelmaking engendered various myths, and the unification and restoration of order to Britain in the wake of the Roman retreat was symbolized by one of the most enduring of these: Excalibur, the legendary sword of King Arthur, sometimes attributed with magical powers and associated with the rightful sovereignty of Britain. At a time when swords regularly snapped in battle, leaving a knight defenseless, it is easy to see why a high-quality steel sword wielded by a strong warrior came to represent the rule of civilization over chaos. The fact that the process of making steel was, necessarily, highly ritualized also helps to explain why this material came to be associated with magic.

This was nowhere more true than in Japan, where the forging of a samurai blade took weeks and was part of a religious ceremony. The *Ama-no-Murakumo-no-Tsurugi* ("Sword of the Gathering Clouds of Heaven") is a legendary Japanese sword which allowed the great warrior Yamato Takeru to control the wind and defeat all his enemies. Despite the fantastic stories and rituals, the idea that some swords could be made ten times stronger and sharper than other swords was not just a myth, but a reality. By the fifteenth century AD the sword steel made by the samurai of Japan was the best the world had ever seen and remained preeminent for five hundred years until the advent of metallurgy as a science in the twentieth century.

These samurai swords were made from a special type of steel called *tamahagane,* which translates as "jewel steel," made from the volcanic black sand of the Pacific (this consists mostly of an iron ore called magnetite, the original material for the needle of compasses). This steel is made in a huge clay vessel four feet tall, four feet wide, and twelve feet long called a *tatara.* The vessel is "fired"—hardened from molded clay into a ceramic—by lighting a fire inside it. Once fired, it is packed meticulously with layers of black sand and black charcoal, which are consumed in the ceramic furnace. The process takes about a week and requires constant attention from a team of four or five people, who make sure that the temperature of the fire is kept high enough by pumping air into the *tatara* using a manual bellows. At the end the *tatara* is broken open and the *tamahagane* steel is dug out of the ash and remnants of sand and charcoal. These lumps of discolored steel are very unprepossessing, but they have a whole range of carbon content, some of it very low and some of it high.

The samurai innovation was to be able to distinguish high-carbon steel, which is hard but brittle, from low-carbon steel, which is tough but relatively soft. They did this purely by how it looked, how it felt in their hands, and how it sounded when struck. By separating the different types of steel, they could make sure that the low-carbon steel was used to make the center of the sword. This gave the sword an enormous toughness, almost a chewiness, meaning that the blades were unlikely to snap in combat. On the edge of the blades they welded the high-carbon steel, which was brittle but extremely hard and could therefore be made very sharp.

By using the sharp high-carbon steel as a wrapper on top of the tough low-carbon steel they achieved what many thought impossible: a sword that could survive impact with other swords and armor while remaining sharp enough to slice a man's head off. The best of both worlds.

No one could create stronger and harder steel than the samurai until the Industrial Revolution. When at this time European countries first started to build structures on a larger, more ambitious scale — such as railways, bridges, and ships — they used cast iron, because it could be made in large quantities and poured into molds. Unfortunately it was extremely prone to fracture under certain conditions. As engineering became more ambitious, those conditions came about more often.

One of the worst accidents occurred in Scotland. On the night of December 28, 1879, the world's longest bridge, the cast-iron Tay Rail Bridge, collapsed during a powerful winter gale. A train carrying seventy-five passengers plunged into the River Tay, killing all of them. The disaster confirmed what many suspected, that iron just wasn't up to the job. What was needed was the ability not just to make steel as strong as samurai swords but to mass-produce it.

One day a Sheffield-based engineer named Henry Bessemer stood up at a meeting of the British Association for the Advancement of Science and announced he had done it. His process didn't require the elaborate procedures of the samurai. He could create tons of liquid steel. It was a revolution in the making.

The Bessemer process was ingeniously simple. It involved blowing air through the molten iron, so that the oxygen in the air would react with the carbon in the iron and remove it as carbon dioxide gas. It required a knowledge of chemistry that for the first time put steelmaking on a scientific footing. Moreover, the reaction between the oxygen and the carbon was extremely violent and gave off a lot of heat. This heat raised the temperature of the steel, keeping it hot and liquid. The process was straightforward and could be used on an industrial scale; it was the answer.

The only problem with the Bessemer process was that it didn't work. Or at least that was what everyone who tried it said. Soon, angry steelmakers, who had bought the license from Bessemer and invested large sums of money in equipment only to produce brittle iron, started asking for their money back. He had no answers for them. He didn't really understand why the process was successful sometimes and unsuccessful at others, but he continued to work on his technology, and with the help of the British metallurgist Robert Forester Mushet he adapted his technique. Rather than trying to remove the carbon until just the right amount was left, about 1 percent, Mushet suggested removing all the carbon and then adding 1 percent carbon back in. This worked and was repeatable.

Of course, when Bessemer tried to interest the world in this new process, the other steelmakers ignored him, assuming that it was yet another swindle. They insisted that it was impossible to create steel from liquid iron, and that Bessemer was a con artist. In the end he saw no option but to set up his own steel works and just start making the stuff himself. After a few years the firm of Henry Bessemer & Co. was manufacturing steel so much more cheaply and in such larger quantities than his rival firms that they were eventually forced to license his process, in the end making him extremely rich and ushering in the machine age.

Could Brian be another Bessemer? Could he have stumbled across a process for reorganizing the metal crystal structure at the tip of a razor blade through the action of electric or magnetic fields, a process he didn't understand but that worked nevertheless? There are many stories of those who have laughed at visionaries only to be embarrassed by their subsequent success. Many laughed at the idea that heavier-than-air flying machines were possible, and yet we all fly around in them. Likewise, television, mobile phones, computers—all have emerged from a cloud of derision.

Until the twentieth century, steel razors and surgical knives were extremely expensive. They had to be hand-made from the highest-grade steel since only this type of steel could be sharpened sufficiently to cut facial hair cleanly and effortlessly, without snagging. (Anyone who has used a blunt razor will know all too well how acutely painful even the slightest snag can be.) And because steel corrodes in the presence of air and water, cleaning the blades blunts them too, as the fine cutting edge literally rusts away. Thus for thousands of years the ritual of shaving began with the process of stropping: the act of sharpening the blade by playing it back and forth along a length of leather. You might think it not credible that a material as soft as leather can sharpen steel, and you would be right. It is the fine ceramic powder that is impregnated in the leather strop that does the sharpening. Traditionally a mineral called jewelers' rouge was used, but these days diamond powder is more common. The act of running the steel along the strop, in a flip-flop manner, causes the blade to meet the hard particles of diamond that are in the powder, which remove very small amounts of metal in the collision, restoring the delicately fine cutting edge.

But this changed when, in 1903, an American businessman called King Camp Gillette decided to use the new cheap industrial steel produced by the Bessemer process to create a disposable razor. This was to be the democratization of shaving. His vision was to eliminate the need to sharpen the blade by making it so cheap that when it became blunt you could simply throw it away. In 1903 Gillette sold 51 razors and 168 blades. The following year, he sold 90,884 razors and 123,648 blades. By 1915, the corporation had established manufacturing facilities in the United States, Canada, England, France, and Germany, and razor blade sales exceeded seventy million. The disposable steel razor became a permanent fixture of every bathroom, and people stopped needing to go to the barber's for a shave. And it has remained so: while there are any number of back-to-basics movements in food production, no one wants to have their hair cut with a copper knife or their face shaved with a blunt razor.

Gillette's business model was clever for many reasons, one of which was undoubtedly that even if the razors were not blunted through the act of shaving they would lose their edge quickly through rusting, assuring repeat business. But there was one further twist to the tale, an innovation so outrageously simple that it had to be discovered by accident.

In 1913, as the European powers were busily arming themselves for the First World War, Harry Brearley had the job of investigating metal alloys in order to create improved gun barrels. He was working in one of Sheffield, England's metallurgy labs, adding different alloying elements to steel, casting specimens, and then mechanically testing them for hardness. Brearley knew that steel was an alloy of iron and carbon, and he also knew that lots of other elements could be added to steel to improve or destroy its properties. No one at the time knew why, so he proceeded by trial and error, melting steels and adding different ingredients in order to discover their effects. One day it was aluminum, the next it was nickel.

Brearley made no progress. If a new specimen turned out not to be hard, he chucked it in the corner. His moment of genius came when after a month he walked through the lab and saw a bright glimmer in the pile of rusting specimens. Rather than ignoring it and going to the pub, he fished out this one specimen that had not rusted and realized its significance: he was holding the first piece of stainless steel the world had ever known.

Accidentally, by getting the ratios of two alloy ingredients right, carbon and chromium, he had managed to create a very special crystal structure in which the chromium and carbon atoms were both inserted inside the iron crystals. The addition of chromium had not made the steel harder, hence he had rejected the sample, but it had done something much more interesting. Normally when steel is exposed to air and water, the iron on the surface reacts to form iron(III) oxide, a red mineral commonly known as rust. When this rust flakes off, it exposes another layer of the steel to further corrosion, which is what makes rusting such a chronic problem for steel structures, hence the need to paint steel bridges and cars. But with chromium present something different happens. Like some hugely polite guest, it reacts with the oxygen before the host iron atoms can do so, creating chromium oxide. Chromium oxide is a transparent, hard mineral that sticks extremely well to steel. In other words, it doesn't flake off and you don't know it is there. Instead it creates an invisible, chemically protective layer over the whole surface of the steel. What's more, we now know that the protective layer is self-healing; when you scratch stainless steel, even though you break the protective barrier, it re-forms.

Brearley went on to try to make the world's first stainless steel knives, but immediately ran into problems. The resulting metal was not hard enough to make a sharp edge, and they were soon dubbed "knives that would not cut." This lack of hardness was, after all, the very reason that Brearley had rejected the alloy for use in gun barrels. Its lack of hardness allowed the alloy to do other things, though, which only became apparent later in the century—namely, it could be formed into complex shapes, leading eventually to one of the most influential pieces of sculpture, present in almost every house: the kitchen sink.

Stainless steel sinks are indomitable and gleaming and seem able to take anything that is thrown at them. In a world where we are keen to dispose of waste instantly and conveniently—from fat, to bleach, to acid—this material has really come through for us. It has ousted ceramic sinks from the kitchen, and would oust the ceramic bowl from the bathroom if we would let it, but we do not yet trust this new metal quite enough for that most intimate of waste disposal jobs.

Stainless steel is the very epitome of our modern age. It is clean-looking and shiny, appears almost indestructible, but is ultimately democratic: in less than a hundred years it has become the metal with which we are the most closely acquainted; after all, we put it in our mouths almost every day. For, in the end, Brearley did manage to create cutlery from stainless steel, and it's the transparent protective layer of chromium oxide that makes the spoon tasteless, since your tongue never actually touches the metal and your saliva cannot react with it; it has meant that we are one of the first generations who have not had to taste our cutlery. It is often used in architecture and art precisely because its bright surface appears uncorrodable. Anish Kapoor's *Cloud Gate* sculpture in Chicago is a good example. It reflects back to us our feeling of modernity, of being clinical, and of having conquered grime, and the dirt and messiness of life. Of being indomitable ourselves.

By solving the problem of making stainless steels hard enough for cutlery, metallurgists also unwittingly solved the problem of razors rusting, thus creating the finest cutting blade the world has ever known, and in the process altering the appearance of so many faces and bodies. Inadvertently, this domestication of shaving has also created a weapon of choice for street crime: razors that are both durable and cheap, but more than that, ultra-sharp—able to slice through several layers of leather, wool, cotton, and skin, as I knew all too well.

I weighed all this up as Brian and I talked about his new process for sharpening stainless steel razor blades. As stainless steel, a hard, tough, sharp steel impervious to water and air, has been created mostly through trial and error over the last few thousand years, it didn't seem utterly impossible that someone, even without scientific training, might yet stumble across a process for resharpening a razor blade. The microscopic world of materials is so complex and huge that only a fraction of it has been explored.

At the end of the evening, as we both left the pub, Brian shook my hand and told me he would be in touch. As he staggered off down the Dublin road bathed in the yellow light of the sodium street lamps, he turned and shouted drunkenly: "Hail to the god of steel!" I assumed he meant Hephaistos, the Greek god of metals, fire, and volcanoes, whose classical image is that of a smith at a forge. Physically handicapped, he is misshapen, suffering probably from arsenicosis, an infliction common to smiths of the time, who were exposed to high levels of arsenic poisoning during the smelting of bronze, which resulted in lameness and skin cancers. I looked back at Brian as he staggered down the road—with his walking stick and his red face—and, not for the first time that evening, wondered who he really was.