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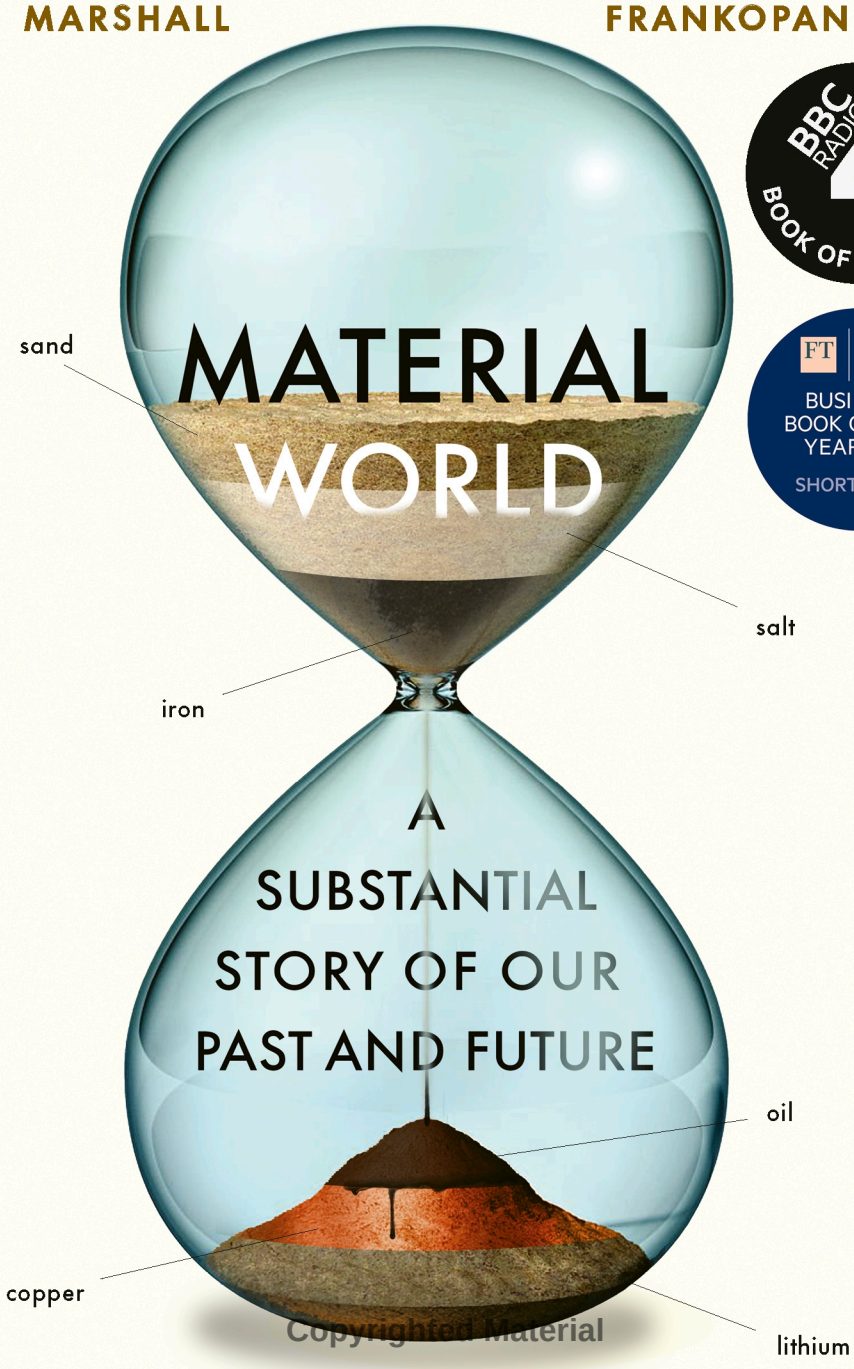
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A SUBSTANTIAL STORY OF OUR PAST AND FUTURE



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Contents

Introduction 1

PART ONE Sand

1 *Homo Faber* 27
2 Built upon Sand 63
3 The Longest Journey 87

PART TWO Salt

4 Salt Routes 125
5 Salt of the Earth 143
6 The Fire Drug 163
Postscript: Many Salts 177

PART THREE Iron

7 You Don't Have a Country 195
8 Inside the Volcano 214
9 The Last Blast 233

PART FOUR Copper

10 The Next Greatest Thing 251
11 The Hole 265
12 The Deep 290

PART FIVE Oil

13 The Elephant 309
14 Pipes 327

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15 The Everything Thing 344
Postscript: Peak Oil 361

PART SIX Lithium

16 White Gold 371
17 Jelly Rolls 397
18 Unmanufacturing 413

Conclusion 425

Notes 445
Bibliography 461
Acknowledgements 471
Index 475

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Introduction

I was standing on the edge of a precipice looking down into the deepest hole I had ever seen. At the bottom was a group of people in hard hats, or at least so I was told; they were much too far to make out with the naked eye. In the ground near them were hundreds of pounds of high explosive. This was enough, I was informed, to demolish a city block.

In front of me was a metal panel with two buttons, and next to me was a man with a walkie-talkie. We were listening in to the control room where someone was counting down. I had been told to press the two buttons simultaneously when the countdown reached zero. The charge from the detonator would take a split second to reach the bottom of the pit, at which point a football pitch-sized square of the Nevada dirt would evaporate before our eyes.

'You'll feel the shockwave first,' said the man with the walkie-talkie. 'Then you'll see the earth going up, then you'll hear the explosion. In that order. It's kinda weird.'

I hadn't travelled out into the high desert to set off a bomb; I had come because of a spreadsheet. Some months earlier, scanning through Britain's trade statistics, I had noticed something odd: flows of gold were distorting the figures, and hence our picture of the nation's economy. Gold, it turned out, had briefly overtaken cars and pharmaceuticals as the UK's biggest export.

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Given Britain does not have a gold-mining industry this was perplexing. How could a country with no significant gold reserves become one of its biggest producers? As far as I could make out, part of the answer was that much of the world's physical gold passes through London on its way somewhere else. In order to solve the riddle I travelled out to where the precious metal is actually extracted, to chart the journey of gold from the ground to the refinery and then, in the form of bars of bullion, around the world. But as we began filming it dawned on me that there was an even more intriguing story to tell, one that says rather a lot about humankind's relationship with the world.

It had taken some months for my producer to persuade the miner in question, Barrick Gold Corporation, to open its doors, and a few days to get there from London. The Cortez mine is not the kind of place you happen upon accidentally. In our case it took two flights and a four-hour drive west across the salt flats of Utah, followed by another two-hour car journey with Barrick's minders. There was a highway, mostly empty except for the occasional heavy truck, then a long desert road, then a dirt track winding into a long, dry uninhabited valley. Cowboy country.

The mine itself is located on the slopes of a hill called Mount Tenabo, a sacred site for the tribespeople of the Western Shoshone. The process of mining is comparatively simple, and echoes the techniques used by gold miners back in the nineteenth century, albeit at a gargantuan scale. The rocks are blasted out of the earth, crushed and then ground into a fine dust, and eventually mixed with a cyanide solution which helps separate out the gold itself.

This is the reality of twenty-first-century resource exploitation: reducing vast quantities of rock into granules and chemically processing what remains. It is both awe inspiring and disturbing. One risk is that the cyanide and mercury used in the method could escape into the surrounding ecosystem. After

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all, while miners like Barrick insist they follow all the rules laid down by the US Environmental Protection Agency (EPA), campaigners warn that pollution often finds its way out of the mine. Indeed, a few years earlier the EPA had fined Barrick and another nearby miner $618,000 for failing to report the release of toxic chemicals including cyanide, lead and mercury. But the main thing I was struck by as I observed each stage in this process was just how far we will go these days to secure a tiny shred of shiny metal.

The scale, for one thing, was mind-boggling. As I looked down into the pit I could just about make out some trucks on the bottom, but only when they emerged at the top did I realise that they were bigger than three-storey buildings; the tyres alone were the size of a double-decker bus. How much earth do you have to remove to produce a gold bar? I asked my minders. They didn't know, but they did know that in a single working day those trucks would shift rocks equivalent to the weight of the Empire State Building. Later on I did the sums for myself. For a standard gold bar (400 troy ounces) they would have to dig about 5,000 tonnes of earth. That's nearly the same weight as ten fully laden Airbus A380 super-jumbos, the world's largest passenger planes – for one bar of gold.

Perhaps you already knew this is how gold is mined these days – that it doesn't come out of the earth in nuggets or as a rich seam forged by Mother Nature. Perhaps you knew that it is instead the product of a chemical reaction involving one of the most toxic cocktails known to humankind, that it's extracted not by burrowing in the earth so much as by tearing down entire mountains. Perhaps I was naive but I, for one, hadn't quite realised.

As I looked down into the open pit at the house-sized trucks and the miners scurrying like ants around the blast site, I started

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to feel a little queasy. It wasn't just the spectacle in front of me – it was something I was wearing on my finger.

Some months earlier I had got married. My wife and I stood in front of our family and friends and exchanged gold rings as a token of our love. As the countdown continued on the walkie-talkie beside me, I thumbed the ring and pondered. The chances were it was probably extracted from the ground through precisely the same techniques I was now witnessing. Why hadn't I checked where it came from? I made a point of checking the diamonds in my wife's engagement ring weren't conflict diamonds, so why didn't I find out what was sacrificed, by man and land, for the gold? Later I would learn that while it might once have taken about 0.3 tonnes of ore, extracted via more traditional mining methods, to obtain enough gold for a typical wedding ring, these days it might take between 4 and 20 tonnes of rock. Standing there with the detonator in front of me, I felt like someone who has just enjoyed a slap-up sausage and egg breakfast before being shown around the abattoir.

Then there was the mountain itself. The pit I was staring into was not just somewhere near Mount Tenabo. It was Mount Tenabo. The mine was literally being dug into the shoulders of the peak. As I looked across to the other side of the hole I could count layer upon layer of multicoloured rock strata constituting the internals of this mountain. I don't believe in the water gods the Indigenous Western Shoshone tribes worship but even so it was hard not to feel there was something, well, brutal and significant about peeling away the skin of the soil and peering beneath the surface.

As the countdown continued I turned around and looked desperately towards my producer. 'Would you like the honour?'

She looked at me in disbelief and then took my place. Shamefacedly I stepped back and watched.

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The countdown reached zero. 'Firing shot one, Cortez Hills,' said the man into the walkie-talkie, and pointed at the buttons. She pressed them both. There was a momentary pause – a second or so. Then a wave of pressure hit us – nothing dramatic, more like a waft of air. Then the ground was shaking and I looked down hundreds of feet towards the bottom of the pit where the earth had turned to liquid. The explosion rippled along the base of the mine, casting dirt and smoke up into the air. Only then did we hear the rumble. It boomed and echoed around the valley for what felt like minutes.

The economist John Maynard Keynes once called gold a 'barbarous relic'. His point was that while it might look pretty on a necklace or inside a sarcophagus it doesn't really do all that much.

Clearly it has value – why else would we blow up entire mountains for a few bars of it? But think, for a moment, about what gold actually *does*. It plays an important if somewhat fringe role in electronics and chemistry, but that accounts for less than a tenth of demand these days. Instead, its primary uses are in jewellery, decoration and as an asset for those who worry about economic disaster. Some of the gold I saw being mined in Nevada is probably now on someone else's ring finger. Or it might just as plausibly be back underground again, this time in the form of a bar in a bank vault. Sacrilegious as this will sound to jewellers and jumpy investors, the world would probably not cease to function, nor civilisation grind to a halt, if we suddenly ran out of gold.[1]

So in the months after I returned from Nevada I kept returning to a few questions. If this is what it takes to extract a metal we could mostly live without, then what does it take to extract those materials we *really* need? Come to mention it, what *are* the materials we really depend on? What are the physical ingredients

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without which civilisation really would grind to a halt, and where do they actually come from?

I had a hunch that steel would have to be among them. Most buildings and cars – not to mention the machines with which we build everything else too – are made from this alloy of iron, carbon and a few other crucial elements. Nor could we create modern spaces without concrete. Copper was surely essential, given it underpins the electrical networks upon which we depend. Since we still rely on fossil fuels for so much of our energy they would, I guessed, qualify as essential materials too – though perhaps one should also consider something like lithium, the element at the heart of all those batteries we will need in future. But how is one to quantify our dependence on these materials? And did their extraction invariably involve the same species of destruction I had witnessed at the Cortez mine?

Economics, the discipline in which I have been immersed for most of my professional life, seemed to have few definitive answers to these sorts of questions. Something's value is what someone is willing to pay for it, goes the standard explanation. If something is in short supply, people will cut back, find a suitable substitute (if such a thing exists) and move on. End of story.

Yet the story doesn't seem to accord with the reality, because this stuff clearly matters. For all that we are told we live in an increasingly dematerialised world, where ever more value lies in intangible items – apps and networks and online services – the physical world continues to underpin everything else. This is not especially evident when you glance at the balance sheets of our economies, which show that, for instance, four out of every five dollars generated in the US can be traced back to the services sector and an ever vanishing fraction is attributed to energy, mining and manufacturing. But pretty much everything from

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social networks to retail to financial services is wholly reliant upon the physical infrastructure that facilitates it and the energy that powers it. Without concrete, copper and fibre optics there would be no data centres, no electricity, no internet. The world, dare I say, would not end if Twitter or Instagram suddenly ceased to exist; if we suddenly ran out of steel or natural gas, however, that would be a very different story.

We all know this instinctively. And such principles are self-evident during periods of war, shortage or financial meltdown. Yet as far as all-important statistics like gross domestic product (GDP) are concerned a dollar is a dollar, whether it is spent on Facebook or on food. There is a logic and elegance to this, but it didn't exactly answer my questions. It is all very well knowing the *price* of something, but price is not the same thing as *importance*.

This book started off as my attempt to answer these questions – a meditation not so much on the market value of substances but our *dependence* upon them. But as I journeyed deeper, beyond my comfort zone of conventional economics, it became something else: a story of wonder. For the more I understood about these materials – commonplace, humdrum and often, yes, cheap – the more magical they appeared to be.

Consider something as simple as a grain of sand. There is no element in the earth's crust, save for oxygen, which is more commonplace than sand's main ingredient – silicon. Yet kneel down and examine what's in the ground and you soon realise that you are sinking into a universe of complexity. There are coarse, angular grains, perfect for construction. There are marine sands sitting on the seafloor until they are dredged up and turned into new land. There are desert sands, so worn by the wind that when you study them under a microscope you see what looks like a pile of marbles – the edges of the grains rounded down by thousands

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of years of erosion. There are sands left behind by ancient tropical oceans of such purity that they are traded around the world.

Mix sand and small stones with cement, add some water and you have concrete, quite literally the foundational material for modern cities. Add it to gravel and bitumen and you have asphalt, of which most roads are made – those that aren't made of concrete, that is. Without silicon we would not be able to make the computer chips that support the modern world. Melt sand at a high enough temperature with the right additives and you make glass. Glass – plain, simple glass – is, it turns out, one of the great mysteries of material science; neither liquid nor solid with an atomic structure we still do not entirely understand. And the glass you have in your windscreen is just the beginning of it, for, woven into strands and accompanied by resin, glass becomes fibreglass: the substance out of which wind-turbine blades are made. Refined into pure wires, it becomes the fibre optics from which the internet is woven. Add lithium to the mix and you get a strong, resilient glass; add boron and you get something called borosilicate glass.

You will have encountered borosilicate glass before, probably under the brand name the manufacturer Corning gave it: Pyrex. Stable, clear and robust, capable of withstanding a wide range of temperatures, from the naked flame of a Bunsen burner to the piercing cold of deep space, borosilicate glass is one of the unsung heroes of the modern age. Unlike regular glass, which when exposed to potent chemicals can leach small particles into the liquid, borosilicate glass remains chemically inert, making it the perfect material for test tubes, lab beakers and medical vials. The one thing almost every medicine or vaccine in history – including those developed for COVID-19 – has in common is the borosilicate containers in which they were worked on, stored and transported.

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But we tend not to pay much attention to these kinds of things until we run short of them. That was certainly the case with borosilicate glass, which received a sudden flurry of interest in the wake of the COVID pandemic, amid worries that the main thing holding back the distribution of vaccinations might not be the pharmaceuticals themselves but the containers in which they would be shipped. In the event, thousands of workers along a complex supply chain stretching from mines to refineries to factories helped avert disaster. Corning even deployed an entirely new type of glass, made not with boron but with aluminium, calcium and magnesium, to help satisfy the demand for medicinal vials.

Other sectors were not so fortunate. In the pandemic and thereafter, there were shortages of face masks, of swabs and diagnostic reagents, shortages of cement and steel, of timber and toilet paper, of industrial gases and chemicals, shortages of meats, of mustards, of eggs and dairy. There was such a shortfall of silicon chips – semiconductors as they are often called – that car manufacturers across the world had to down tools and shutter their plants. Computer and smartphone manufacturers were unable to fulfil orders. Even a year after their launch, the new generation of games consoles was still in short supply. Only after around two years did those shortages come to an end.

The funny thing about these supply chain crises was that each of them seemed to take the world's governments and policymakers by complete surprise. They were surprised that there was a shortage of semiconductors, that cars needed so many of them and that the shortage of new cars would push second-hand car prices up to record highs.

The UK government was similarly startled in late 2021 when it suddenly ran short of carbon dioxide and discovered that without CO_2 the food industry is unable not merely to make

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sparkling drinks fizzy but also to preserve and store foods, as well as to stun pigs and chickens before slaughter. This could all be traced back to the sudden closure of two fertiliser plants in Cheshire and Teesside. The majority of Britain's CO_2 supplies came, it turned out, from these two sites whose primary purpose was to make something else altogether: ammonia. And since natural gas prices were high and since ammonia is made, as we shall see in the following chapters, from natural gas, a lurch in one price had caused a sudden shortage in another, seemingly unrelated substance.

But should this *really* all have come as such a surprise? For a clue about the answer, consider a famous essay written in 1958 by Leonard Read, an American economist, called 'I, Pencil'. 'I am a lead pencil,' it begins, 'the ordinary wooden pencil familiar to all boys and girls and adults who can read and write.' Yet, continues Read, or rather the pencil, 'not a single person on the face of this earth knows how to make me'.[2]

The wood in the pencil comes from cedars growing in western America, sawn down with steel made in blast furnaces and finished in workshops. It is milled into slats and dried and dyed and dried again, and the slats are grooved and glued into place. The lead in the pencil's core is graphite mined in Sri Lanka, refined and mixed with clay from Mississippi, alongside chemicals made from animal fat and sulphuric acid. The wood and lead of the pencil are coated in lacquer made from castor oil derived from castor beans, resins are used to label it, and it is capped on its base with brass made from copper and zinc, mined on the other side of the world. The eraser is made from rapeseed oil from Indonesia, with numerous chemicals along the way, from sulphur chloride to cadmium sulphide.

All for that simplest of things, a pencil. Yet from the manufacturers who worked on each ingredient to the hauliers who

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shipped the parts to those working in power stations providing the energy for the process, 'millions of people', writes Read's pencil, 'have had a hand in my creation, no one of whom even knows more than a very few of the others'.

There are a couple of straightforward lessons here. The first is how little we understand about how everyday products are actually made. The second is that, given all this complexity, no single human being could carry out, or for that matter direct, these numerous processes. For obvious reasons 'I, Pencil', written at the height of the Cold War, put most of the emphasis on the second of those lessons. Read's essay was championed by the free market economist Milton Friedman as an illustration of why his Soviet counterparts were wrong to try to run their economy via central planning committees.

Yet as I contemplated the breakdown in twenty-first-century supply chains, it struck me that we might have done just as well to remember the first of those lessons. Surely if we spent a little more time contemplating how the items upon which we rely actually get produced, we might not be so baffled when they run short. Thanks to Read's essay, millions of economics students now know their way around the supply chain of a pencil, but what about a smartphone or a vaccine or a battery? What about the supply chain for carbon dioxide or borosilicate glass?

These networks of people and expertise, turning raw materials into sophisticated products and then delivering them to us, stand alongside the substances themselves as the other star of this book. In the following pages you will find a celebration of how networks of humans, most of whom do not know each other, can collaborate to turn seemingly unpromising, inert substances into things of wonder. And few supply chains, I discovered, are quite as wondrous as those producing silicon chips.

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Long before the chip shortage, I had undertaken to try to tell the story of a grain of silicon, all the way from the quarry through to the semiconductor foundry and assembly plant where it would become part of a smartphone. I soon realised that, much as with Read's pencil, no single person, even those working on the supply chain itself, could fully explain to me the processes – even the very simplified processes – that took place at each stage along this journey. Those working at foundries understood plenty about photolithography and chemical abrasion, but little about how the ultra-pure silicon wafers they were working on were actually made. No one at the quarry digging quartzite from the ground (the chips, it turns out, begin their lives not as grains of sand but as fist-sized lumps of stone) understood much about its eventual destiny.

Yet most striking of all was the extraordinary length and drama of this journey. Between being blasted out of the ground in a quarry and ending up inside a smartphone, this grain of silicon will have circumnavigated the world numerous times. It will have been heated to more than 1,000°C and then cooled, not once or twice but three times. It will have been transformed from an amorphous mass into one of the purest crystalline structures in the universe. It will have been zapped with lasers powered by a form of light that you can't see and doesn't survive exposure to the atmosphere. This – the process of turning silicon into a tiny silicon chip – was the most extraordinary journey I had ever traced.

But this was just the beginning. Over the following months I would see more quarries. I would descend to the sweltering depths of the deepest mine in Europe. I would see where salt comes from and how it gets transformed into the chemicals without which we would all struggle to survive. I saw red rock being turned into molten metal and then hammered into steel.

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I travelled to eerie green pools from where we get lithium and followed the substance as it was pasted and rolled and squeezed into a battery for an electric car. And the more I travelled, the more I realised that I had spent most of my life inhabiting another world altogether, a place I came to think of as the ethereal world.

Perhaps you live there too: it is a rather lovely place, a world of ideas. In the ethereal world we sell services and management and administration; we build apps and websites; we transfer money from one column to another; we trade mostly in thoughts and advice, in haircuts and food delivery. If mountains are being torn down on the other side of the planet, it hardly seems especially relevant here in the ethereal world.

When I flew out to Nevada to film that mountain being exploded I was really looking to film a visual metaphor, to turn the physical into something ethereal: a news report that would help people understand an idea like trade flows that bit better. Standing at the edge of the pit there, though, it occurred to me that my perspective had been dangerously shallow. All of a sudden I realised I was staring out from the brink of one world and into another: the Material World.

The Material World is what undergirds our everyday lives. Without this place your beautifully designed smartphone wouldn't switch on, your brand new electric car would have no battery. The Material World will not provide you with a gorgeous home, but it will ensure your home can actually stand up. It will keep you warm, clean, fed and well, however little heed you may pay it.

The Material World is where you will find the most important companies you've never heard of, companies like CATL, Wacker, Codelco, Shagang, TSMC and ASML. These names may mean nothing to you, but they are just as important, perhaps more important, than the familiar brands everyone has heard of – the

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Walmarts, Apples, Teslas and Googles of this world. For the best-kept secret of the modern economy is that these world-famous brands depend entirely on the obscure firms of the Material World to make their products and help their clever ideas, well, materialise. It is where ideas become a tangible reality.

Why are today's megabrands so happy to rely on other companies to get the real work done? Partly, frankly, because operating in the Material World, where you have to dig and extract stuff and turn it into physical products, can be a difficult, dangerous, dirty business. In the following pages we will witness how far twenty-first-century humanity is willing to go for these materials, whether that means digging a hole as deep as a canyon or scouring the bottom of the ocean to discover metals of concentrations richer than anything that exists on dry land.

That brings us to perhaps the most dangerous of all the myths that predominate the ethereal world – the idea that we humans are weaning ourselves off physical materials. Some economists point to data in the US and UK showing that we are consuming ever fewer resources for each dollar or pound of income we generate. While for most of human history our economic output closely tracked our exploitation of natural resources – and for that matter our energy use – in the past couple of decades these two lines have diverged: GDP kept on rising while our use of such resources plateaued. This, they say, is cast iron proof that we are getting 'more from less'.[3]

It is an appealing idea – especially with the world's climate heating up and everyone casting around for good news – but having just witnessed a sacred mountain being destroyed for something we don't exactly need, I was a little sceptical. Was there a chance, I wondered, that we were instead simply outsourcing all this dirty stuff to a different place where we didn't have to think about it? In short, to the Material World?

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I probed a little more, and discovered that while material consumption is certainly falling in post-industrial nations like the US and UK, on the other side of the world, in the countries whence Americans and Britons import most of their goods, it is rising at a breakneck rate. Indeed, gold mines in Nevada are the barest fraction of it. We go to far more extraordinary lengths to extract copper and oil, iron and cobalt, manganese and lithium from the ground. We dig for sand, for rock, for salt, for stone. And we do so at an astonishing rate. Far from being a sideshow, this activity is getting more important, not less. The most topical example of this comes back to climate change. It's a crucial irony that pursuing our various environmental goals will, in the short and medium term, require considerably more materials to build the electric cars, wind turbines and solar panels needed to replace fossil fuels. The upshot is that in the coming decades we are likely to extract more metals from the earth's surface than ever before.

Yet this is only the latest chapter in a long saga. This stuff is happening *already*. In 2019, the latest year of data at the time of writing, we mined, dug and blasted more materials from the earth's surface than the sum total of everything we extracted from the dawn of humanity all the way through to 1950. Consider that for a moment. In a single *year* we extracted more resources than humankind did in the vast majority of its history – from the earliest days of mining to the industrial revolution, world wars and all. Nor was 2019 a one-off. In fact, you could have said precisely the same thing about every year since 2012. And far from diminishing, our appetite for raw materials continues to grow, up by 2.8 per cent in 2019, with not a single category of mineral extraction, from sand and metals to oil and coal, falling.

You don't hear about this all that much, or if you do it is primarily through a fossil fuel prism. For all sorts of understandable reasons there is plenty of attention given to the hydrocarbons we

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are still extracting. You will probably already know that we have, for decades, been mining enormous amounts of coal and oil from under the earth's surface. You will probably realise that we are now gradually beginning to wean ourselves off these fuels – or rather we are slightly slowing the rate at which we extract them from the ground.

You might presume, then, that this means our broader appetite for minerals is diminishing. Not a bit of it. For it turns out oil and other fossil fuels have only ever represented a fraction of the total mass of resources we're extracting from the earth. For every tonne of fossil fuels, we exploit 6 tonnes of other materials – mostly sand and stone, but also metals, salts and chemicals. Even as we citizens of the ethereal world pare back our consumption of fossil fuels we have redoubled our consumption of everything else. But, somehow, we have deluded ourselves into believing precisely the opposite.

My hunch is that this partly comes back to data – or lack of it. We are very good at counting dollars of GDP, but our understanding of how much *stuff* we are pulling out from the ground is surprisingly primitive. The United Nations and a few national data bodies such as the Office for National Statistics in the UK have begun in recent years to put together what are known as material flow analyses – measuring the substances we are extracting from the earth, consuming and then recycling or discarding. But this data only tracks the 'material' being mined, not the ten super-jumbo jets' worth of earth and rock displaced to get hold of it. From a statistical perspective, this 'waste rock' – this sacred mountain – is simply never accounted for. Humankind's true footprint on the earth is, in other words, far larger than we realise. And, I would later learn, the footprint of gold mining is dwarfed by that of metals like iron and copper, and they in turn are dwarfed by the sand and stone we dig and blast.

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This urge to obtain minerals has always been among the strongest forces driving humanity. It did not begin or end at Mount Tenabo with the ancestral lands of the Shoshone; it continues from the United States to China to Africa and Europe and even to the depths of the Atlantic Ocean. Yet because it increasingly happens out of sight and doesn't show up in conventional economic data, we are getting ever better at convincing ourselves it's not happening.

It was not always thus. For much of our history governments placed an extraordinary emphasis on the control of these materials. This struggle for control was, as we shall explore, the driving factor behind some of the epochs of history whose legacy we are still attempting to understand and reconcile: empire, colonisation and war. When the Berlin Wall fell, some economists declared that we had begun a new era for global resources – that with the advent of truly global trade and supply chains, the race for materials had come to an end. As a result, many countries, the United States included, began to run down their stockpiles of these crucial minerals, built up over the previous half-century. As trade barriers were lifted, manufacturing became a truly global enterprise, comprised of just-in-time supply chains bestriding the planet.

But today it is rapidly dawning on governments the world over that the control of these materials and processes matters more than ever. One of Joe Biden's first acts upon becoming US president was to sign an executive order on 'America's Supply Chains', to examine where the US was reliant on other countries. For semiconductors, it is the silicon chips whose manufacture we will encounter in the following pages. For batteries, it is a collection of metals including cobalt, nickel, zinc and, most importantly of all, lithium.

This book about the Material World is told through six materials: sand, salt, iron, copper, oil and lithium. Casting these materials

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as the protagonists might seem slightly perverse, given most stories of human progress come from our own perspective. Why do some countries thrive while others fail? Why did the industrial revolution take place in England rather than in Ethiopia? The fashionable view these days is that it mostly comes down to a combination of history, happenstance and having the right kinds of institutions that allow people to innovate and thrive. But this has never been the full story, for the secret of humankind's success is about more than our DNA or our political institutions. Our destiny has invariably been intertwined with what we have extracted from the earth and adapted to our purposes.

While terms like the Stone, the Bronze and the Iron Age are typically used to refer to distant, forgotten eras, actually our reliance on physical tools and materials has exploded rather than diminishing. Given how much sand and rock we still blast from the planet, we are still firmly embedded in the Stone Age. Our need for steel and copper has multiplied in recent years. This, then, is also the Iron Age, not to mention the age of copper, of salt, of oil and lithium.

These six materials are the essential ingredients of the environment in which you're reading this – the battery without which your phone would cease to function, the concrete without which your home's foundations would crumble. These materials rarely feature in stories of human endeavour or innovation, or if they do it is as an inert substance magically transformed by a brilliant inventor.

But it is time now to give these materials their moment in the sun, and to tell our story from their perspective. We might, just about, be able to live without these six materials but we could not thrive without them. They are the substances for which there is, for the most part, no ideal substitute. They helped us build our world, and we would be thrown into chaos if we were to lose

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access to them – indeed, as we will discover, the collapse of some civilisations and the triumph of others can be laid at the door of one or a number of the six.

We will discover how the pursuit of these materials shaped geopolitical history and is beginning to shape its future. We will uncover the uncomfortable consequences for our environment of our insatiable appetite for these materials. At times you will find it an unsettling experience – especially since we are all to some extent complicit, creating the demand for the raw materials we extract from the ground. You might be left with the impression that the best solution is for us all to try to consume less and recycle more, and this, frankly, would be no bad thing.

But towards the end of the book there is also a tantalising glimpse of something else: a world where, for the first time since the industrial revolution, we might be able to sustain ourselves without digging much deeper into the earth and exploding mountains to satisfy our demand for commodities. We will never live in a truly dematerialised world; ever since humans picked up stone and fashioned it into tools we have been exploiting the earth and leaving our mark. But we *can* shrink our footprint. In so doing we could help mitigate the rise of greenhouse gas emissions and confront climate change. The paradox, as you will see, is that getting to that promised land may involve digging and blasting more than we ever have before.

In that promised land, we may no longer rely on fossil fuels, but for the time being we remain hopelessly dependent on them. That became abundantly clear in early 2022 when Russia invaded Ukraine. The invasion pushed up European energy prices to record highs, which in turn fuelled a rise in the cost of living. The scale of the increase took economists by surprise – after all, in the ethereal world it is easy to convince ourselves that we have decoupled ourselves from grimy things like energy and

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raw materials. But one of the lessons you quickly learn when parachuted into the Material World is that in economics nearly everything comes back to energy – even the stuff you least expect. Fertilisers and salts, chemicals and plastics, food and drinks – they are all, to a greater or lesser extent, fossil fuel products.

The events in Ukraine may well speed up our transition towards renewable energy – provided it doesn't push the world back towards coal – but that will raise some fresh challenges. Even as we become less reliant on fossil fuels and petrostates like Russia, we will become more dependent on another more obscure suite of metals from other countries, with which we can build machines to provide us with clean energy. And since renewable energy is so much less energy-dense than fossil fuels or nuclear power, we will have to build many more structures to produce the same amount of energy. So it goes in the Material World.

Why only six materials? Why only sand, salt, iron, copper, oil and lithium? After all, there are hundreds of elements, compounds and materials that play important roles in producing the products we rely on and the services we need in the modern world. Boron never featured on any pandemic preparedness plan, yet getting hold of enough has proved central to the effort to produce and distribute a vaccine for COVID-19 – no easy task given boron is mostly found in a handful of spots with volcanic activity and an arid climate. Nearly a third of the global reserves are in Turkey, with other supplies located in the deserts of California and the Far Eastern reaches of Russia.

Moreover borates, the salts in which the element is found, have plenty of other uses: they are an ingredient in fertilisers, helping seed development and crop yield; they help preserve wood by protecting it from insects and fungal decay. When added to steel, boron can increase its strength; sprinkled into a

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swimming pool, borate salts can help reduce the acidity of the water and prevent the build-up of algae.

Or what about tin, which is both a crucial component in electronic circuit boards and one of the earliest metals our ancestors learned to exploit? What about aluminium, the most common metal in the earth's crust – albeit one we only learned to refine relatively recently? What about platinum and its sister metals such as palladium and rhodium – scarce, important ingredients in electrical components and catalytic convertors? What about chromium, which plays an essential role in the manufacture of stainless steel, or cobalt, or rare earth metals such as neodymium, which goes into precision magnets?

The line I have drawn is as follows: while the six materials that star in this book are not the only important substances in the world, it is hard to imagine modern civilisation without them. We can make batteries without cobalt. We can make headphones and electric motors without neodymium magnets – though they would be bigger and less efficient. The materials in this book are the very hardest to replace.

Albert Einstein was once asked by a group of reporters to explain his theory of relativity. 'I can explain it as follows,' he said. 'It was formerly believed that if all material things disappeared out of the universe, time and space would be left. According to the relativity theory, however, time and space disappear together with the things.' You might say the same thing about the Material World. These substances are the fabric of civilisation. Without them, normal life as we know it would disintegrate.[4]

It is no accident, for instance, that we begin with sand, for this is the material from which humankind has made so much of our environment. It also provides us with a *tour d'horizon* of the Material World. Here, we have the world's oldest manufactured product (glass) and one of its most advanced (semiconductors).

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While sand is the substance from which we make things, salt is a magical material we use to transform things, as well as a vital ingredient for our health and nourishment. The sections on iron and copper are sequenced thus because the story of iron is intertwined with the story of coal while copper is the medium of electricity. Putting them in this order means we cover the first and then the second great energy transitions of the modern age: the adoption of fossil fuels and of electric power. The third and fourth energy transitions are covered in the oil section, which actually features both oil and gas. Having spent much of the book considering the materials which helped bring us the industrial revolutions of centuries gone by, we finish with the material which promises to deliver the next one. Lithium is at the heart of the next energy transition – away from fossil fuels and towards renewable resources.

I have taken a few liberties along the way. Purists may question my decision to lump oil and gas together in one section, or the fact that the salt section does not concern itself purely with sodium chloride, taking a detour into a few other salts besides. And other materials – coal, for instance, and nitrogen-based fertilisers – make regular cameos along the way, even though they are not nominally among the six materials.

Journeying through this world has been the single most fascinating and intellectually exhilarating experience of my career. But it was something else too: unexpectedly therapeutic. As I ventured deeper and researched the primal ingredients of modern life, I began to feel ever so slightly more connected with the world around me. Granted, I was no closer to being able to manufacture a car battery, a sheet of glass or a smartphone, but these objects were no longer complete mysteries to me. Having spent most of my life cosseted in the ethereal world, blissfully ignorant about how we make and get things, I began to look out with fresh eyes.

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My hope is that this book inspires you to take a second look at the world we inhabit, where there is magic in everyday objects and wonder in simple substances.

The six materials described in this book may not be scarce. They may not look or feel particularly sexy. They are not especially valuable in and of themselves. Yet they are the primary building blocks of our world. They have fuelled the prosperity of empires. They have helped us to build cities and tear them down. They have changed the climate and may, in time, help save it. These materials are the unsung heroes of the modern age, and it is time we heard their story.

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PART ONE

Sand

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1

Homo Faber

This story begins with a bang.

An explosion of such magnitude that it would have been audible in two, maybe three continents. Not that there was anyone around to hear it. Because this was roughly 29 million years ago – long before the birth of *Homo sapiens* – somewhere near the modern-day border between Egypt and Libya.

There in the Great Sand Sea desert a meteor pierced the sky and exploded. The force of the blast was truly cataclysmic, enough to create a fireball and a sound that rattled the sabre-toothed cats and apes who roamed the other side of the Mediterranean.

This meteor strike is less well-known than the one that is thought to have done for the dinosaurs 60 million years earlier. As far as we know it did not cause widespread extinctions. Scientists disagree on whether the meteor exploded mid-air or upon impact with the ground and the search for a plausible crater is still ongoing. But the African meteor nonetheless has a special significance, for it provides the most compelling explanation for a mystery story that has puzzled archaeologists and geologists for a century.

Among the treasures discovered with the sarcophagus of Tutankhamen was a necklace depicting the sun god Ra. It was a

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stunning piece of jewellery, subtler but no less beguiling than the iconic gold funeral mask of the Egyptian boy king. This pectoral, as it is sometimes called, was encrusted with precious gems and metals: gold, silver, lapis lazuli, turquoise and carnelian. But at its centre was a beetle carved out of a translucent, canary-yellow stone. All the other gems were familiar but at the time of the tomb's discovery, in the early twentieth century, no one had seen anything like this yellow material before. Why? What was it? And where did it come from? Only when explorers ventured deep into the desert would they begin to find answers.

The Great Sand Sea was so named by Gerhard Rohlfs, a German explorer who in 1873 led an expedition westward into what in Pharaonic times was called the Land of the Dead. A hundred miles after he left the Dakhla Oasis, weeks after setting eyes on any trace of human life, he suddenly encountered an impassable barrier.

'Sand dunes, and sand beyond, truly an ocean of sand,' he wrote. He tried to cross the dunes: impossible, too high, the sand too loose underfoot, even for the camels. He tried to go around them: impossible, for they stretched north and south as far as the eye could see. He marched his team alongside the dunes for weeks, to no avail. Eventually he decided to turn back northwards towards Siwa, the nearest oasis. He and his team wrote a message, put it in a bottle in case they didn't survive the return journey, and built a cairn of rocks over it. If you travel to the Great Sand Sea and pass by the cairn today it is customary to leave your own message in a bottle.

Rohlfs barely survived the return journey. He would surely have perished, in fact, had it not been for an extraordinary stroke of luck. For while returning across one of the world's driest regions, where parts can go without rain for decades, the heavens unexpectedly opened and his crew were able to replenish their

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water supplies. Weeks later this fortunate, emaciated German and his companions reached safety. They brought with them such dismal testimony that no one else bothered attempting the journey for more than 50 years.

Glance at satellite images of this territory and you soon see what he encountered; long, parallel dunes running north to south, separated by flat corridors straight as a Roman road. These perpendicular formations, a product of the prevailing winds, are called seif dunes – after the Arabic word for 'sword' – and some run for nearly a hundred miles. There is a uniformity, a kind of symmetry to them. Except that by the time you've seen the images they are already out of date.

The dunes are constantly on the move, devouring anything that stands in their way. Herodotus once wrote of a Persian prince who sent an army into this desert. Not long after they entered the Great Sand Sea they were engulfed by a sandstorm and were never seen again. Every so often an archaeologist surfaces with supposed evidence of the lost army.

But surveying these dunes from above fails to convey the feeling of standing at their feet. It is not for nothing that most of the early explorers described these formations as living creatures.

'They grow,' wrote Ralph Bagnold, a Briton who explored the Sahara in the 1930s. 'Some . . . can live independently, can keep their shape while moving from place to place, and can even breed.'[1]

Sometimes the seif dunes collapse over escarpments and form into crescent dunes – barchans, as they are known. Sometimes one seif can mount another, and together they form a whaleback, or mega-barchan.

The way these grains interact with each other, the wind and their surroundings seems mysterious and unpredictable, but actually the physics of sand is just incredibly complex. Having

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encountered these dunes as he traversed the deserts, Bagnold devoted the rest of his life to trying to understand them.

Anyone who studies sand dunes labours under Bagnold's long shadow. He became so influential that when NASA was attempting to understand the dunes on Mars it was to Bagnold's books that they turned. Indeed, if you followed the mission of the *Curiosity* rover you may recall that it spent two years exploring Mars's Bagnold Dunes.

Bagnold and a band of fellow explorers were the first people to traverse this desert in the early thirties, finishing the journey Rohlfs had failed to complete half a century earlier. They navigated the seifs in motor vehicles, letting the air out of the tyres of their Model A Fords to drive and surf the loose sand of the dunes. One of Bagnold's colleagues, an Irishman called Pat Clayton, was crossing the lip of one such dune in December 1932 when he suddenly heard a crunching sound beneath his wheels. He got out to investigate and discovered that the desert was covered in great sheets of yellow glass.

Only in the late 1990s did scientists finally confirm that the canary-yellow beetle at the heart of Tutankhamen's necklace was carved from the very same material Pat Clayton had crunched over 500 miles away in the Great Sand Sea. The Egyptian boy king was buried in the Valley of the Gods with a precious stone plucked from the Land of the Dead. This luminous stone was not forged like diamonds, sapphires and other such gems over thousands of years of heat and pressure within the earth's crust. Instead, it was created in the blink of an eye by a falling star. That meteor 29 million years ago had turned the sand into a kind of glass – Libyan desert glass.

There are other forms of glass that occur in nature. Obsidian, a jet-black stone used by our prehistoric ancestors as a tool, is actually a kind of volcanic glass formed by magma as it rapidly cools

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into stone. There are tektites: glassy pebbles created by meteorites or comets smashing into the earth's surface, bits of which then fuse into shiny stones. There are fulgurites: gnarly, hollow tubes you sometimes find on a beach or dune after a lightning strike. But what distinguishes the glass Clayton found there in the desert was that it was utterly, almost unbelievably, pure.

The main ingredient in most sands is silica – silicon dioxide or, as it's sometimes known, quartz. And since glass is, for want of a better phrase, *melted sand*, silica is also the primary ingredient in glass. But that silica content can vary significantly. The glasses we drink from or have in our window panes typically have about 70 per cent silica. The silica content of obsidian and of most tektites is generally between 65 per cent and 80 per cent. The silica content of Libyan desert glass, on the other hand, is a staggering 98 per cent. Not only did this make it the purest naturally occurring glass to have been discovered anywhere, it was purer than anything humankind could create – for the time being at least.[2]

Sand is the great enigma of the Material World.

There is no shortage of the stuff. Heave your way to the top of those dunes and look out over the Great Sand Sea and all you can see is an unending vista of silicon. Silicon in the grains beneath your feet, silicon in the floors of the corridors that separate the seifs, silicon in the Palaeozoic sandstones of the Gilf Kebir on the horizon. After oxygen, which attaches itself to pretty much everything else, silicon is comfortably the most common element in the earth's crust.

Given this ubiquity, it's perhaps unsurprising we've found so many different things to do with it. We dig and quarry and blast more sand out of the earth than any other material. Yet the economic enigma of sand is that in certain guises it is very precious,

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so much so that the European Union deems its purest, most elemental forms a critical raw material.

The earth is made of sand, yet we frequently hear stories of desperate shortages. In some corners of the world there are sand mafias who fight and kill for control of grains of silicon. Under cover of night, renegade crews dig up beaches and riverbeds and smuggle and trade the sand on the black market.

Some sands are prized for their value, some for their beauty, some for the shape of their grains, others for their purity. In Sardinia the authorities have started fining people for removing the iconic white sand from its beaches. At Cleopatra Beach, a bay on an island off the Anatolian coast of Turkey, the unusually white sand is so prized that you must wash it from your feet before leaving, so you do not inadvertently take a single grain away with you. In parts of Asia, river ecosystems are under threat because of excessive dredging as grey-market sand miners attempt to satisfy a seemingly unending appetite for building sand and aggregates. Lives have been ruined and the environment threatened, all in the pursuit of something that appears to be everywhere.

Except that saying it's everywhere is to miss the point, for there are many different types of sand, each with their own unique characteristics. While most sands are primarily silica, some, especially the beautiful white ones on tropical beaches, are composed mainly of something else: the ground-down remains of seashells and corals. Indeed, if you're on a pristine beach in the Caribbean or Hawaii, the chances are that your feet are probably sinking into parrotfish excrement: the fish eat the corals, extract the nutrients, and poop the remaining calcium carbonate on to the seabed. For the most part, the whiter and warmer the beach, the more likely it is to have come out of the bottom of a parrotfish.

The question of what sand is made from is of more than passing consequence. Geologists have something called the

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Udden–Wentworth scale, which dictates that any solid, loose grain of a given size (strictly speaking somewhere between 0.0625mm and 2mm) is a type of sand. Paradoxically, this means that sugar and salt are actually sand. But for our sakes let's ignore the Udden–Wentworth scale and focus primarily on the 70 per cent of sands that are mostly made of silica.

The silica content of sand matters because that ultimately determines what you can do with it. Some sands, including those in the Great Sand Sea, are relatively rich in silica – which is part of the explanation for why Libyan desert glass is so pure. But much of the sand you or I tread on has too little silica and too many impurities to be turned into clear glass or, for that matter, silicon chips. Still: part of what makes sand so enigmatic is that in the wild no two handfuls are alike.

Silicon is a chemical enigma too, metallic yet not quite metal, conductive but only on its own terms. It can be made into a polymer, a plastic. Sand can be gloriously soft to touch but each grain is mightily hard, its astounding strength helping to explain why it is used for the physical foundations of the twenty-first-century world. It is at once the basis of the very oldest and the very newest products humankind has learned how to manufacture. It bookends civilisation.

Sand, you see, is the most ancient and the most modern substance of all. It was our transformation of silicon into beads and cups and jewellery that marked the beginning of the era of *Homo faber* – man the manufacturer. Yet this same substance can be used to create the smartphones and smart weaponry of the twenty-first century.

Here on the beach and in the desert we have our first protagonist. For a long time, chemists sought the key to alchemy – how to turn lead and other unpromising metals into gold. The quest failed, or at least so says the conventional wisdom. But hang on.

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Today we routinely turn silicon into products that are quite literally worth their weight in gold. We forge wondrous products from golden sand.

Given we have learned how to transform a cheap, inert substance into something so valuable, perhaps we shouldn't be shocked that these skills have become so highly prized. When trade wars have erupted, sand has often been at the very centre of them. China's ability to manufacture its own silicon chips to the same extraordinary levels of intricacy as those being made in Taiwan and South Korea is a frequent concern in Washington these days. Will it develop quantum computers faster and with more success than those in the United States?

Since Beijing has surpassed its rivals in so many other economic fields in recent years, Chinese silicon supremacy might feel inevitable, but at least at the time of writing, we are nowhere near there yet. China may be able to dominate global steel, construction, battery and smartphone manufacturing, and even, more lately, social media, but a world-beating semiconductor industry? Not yet.

Why? In part because the process of turning sand into silicon chips is, as we shall see later in this section, among the most extraordinary feats of engineering. Indeed, many of the techniques employed to create transistors so small they are measured in atoms sound so far-fetched that even someone with an overactive imagination would struggle to envisage them. And it is in part because Western leaders will stop at nothing to prevent China from gaining supremacy in this technology. They are determined to prevent the intellectual property, the tools of twenty-first-century alchemy, from escaping. Still, as contemporary as this all sounds, sand has always been at the heart of cutting-edge technology, long before the era of silicon chips.

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For centuries governments vied with each other to control another leading technology derived from sand, a technology that endowed those using it with bionic powers. That technology was glass. Just as today's governments attempt to build up their semiconductor industries and electric car sectors, their predecessors pulled every lever they could, from industrial strategy to industrial subterfuge, to control the trade in glass. In much the same way as scientists are today prevented from smuggling their secrets from the West to Asia, something similar went for the artisans of Murano, the first craftsmen to learn how to make truly clear, thin, beautiful glass. They were threatened with death if they attempted to leave the island in the Venetian lagoon.

When he discovered how to create beautiful crystalline glass, with the help of craftsmen smuggled out of Murano, English glassmaker George Ravenscroft and his workers refused to divulge the secret ingredient (which might have made commercial sense at the time, but looks irresponsible in hindsight, given that his secret ingredient was lead, a toxic metal that can leach into drinks left in a crystal decanter). During the Napoleonic Wars Britain attempted to starve France of glass. In the early days of the United States, English glassmakers were forbidden from emigrating there, by a government determined to protect the domestic industry via regulation and taxes. We often remember the early American colonists' frustration with taxes on tea, but we're much less aware of their frustrations with the British taxes on glass.

So no, there is nothing new about the technology war over silicon. It is a war that has been fought for centuries, between different superpowers across many fronts and many continents. It is a war that has happened in all sorts of unexpected places, including forgotten corners of quiet lands, hundreds of miles from the front line.

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Glass

When they consider humankind's development, economic historians tend to look straight through glass. Why did the industrial revolution happen when and where it did: in Europe in the eighteenth and nineteenth centuries? There are many theories – about the role of political institutions or social and educational mores or geography. Sometimes one or two critical innovations might come up: the steam engine or the blast furnace, for instance. But if you posit that glass might have played a role, you are generally met with a blank stare.

But glass lenses enabled us to peer into space, helping early astronomers such as Galileo discover that the earth orbited the sun. They helped boost the economic might of countries by enabling people to work more; until the invention of lenses, those losing their sight would have to retire early, but thanks to biconvex lenses in spectacle frames, millions of people were able to extend their working lives. No one doubts the importance of breakthrough technologies such as the printing press. But what about the fact that its advent coincided with a mass market for the spectacles which enabled a significant chunk of the literate population to read?

Glass lenses and prisms allowed scientists such as Robert Hooke and Antonie van Leeuwenhoek to create the world's earliest microscopes so they could peer into a world no human had seen before. It was thanks to these glass tools that we learned about the existence of bacteria, of cell reproduction. Glass greenhouses enabled European horticulturalists to bend the climate to their will.

Due to the advent of glass mirrors – before which people were mostly reliant on polished metal surfaces, which reflected barely a fifth of the light – Renaissance artists could suddenly see the

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world from a different perspective. Look through the accounts of early masters such as Leonardo da Vinci and you are left in no doubt about the role played by this new material. The mirror, wrote Leonardo, was the 'master of painters', to be used as a reference tool when painting objects. Indeed, there is a school of thought, articulated most famously by painter David Hockney, that many of the works of the Old Masters could only have been produced with the help of optical aids, including lenses and curved mirrors.[3]

Is it a coincidence that the Renaissance happened in the very locations where affordable and effective mirrors were suddenly available – whether that was northern Italy or Holland? Is it a coincidence that countries which embraced glassmaking would be the very places where the Enlightenment and then the industrial revolution took hold, while regions which abandoned the craft, such as China and much of the Middle East, languished economically in the following centuries? A few years ago two historians, Alan Macfarlane and Gerry Martin, went methodically through 20 of the great experiments that advanced human knowledge – everything from Robert Boyle and Robert Hooke's creation of a vacuum chamber to Isaac Newton's theory of light to Michael Faraday's investigations into electricity – and discovered that all but four of them relied in some way on glass prisms or containers or contraptions.[4]

Glass, in other words, was a foundational innovation, a general purpose technology like the wheel or the steam engine or the silicon chip. This magical product was important not just for what it *was* but for *what it enabled us to do* – to make further leaps of imagination and feats of invention. Indeed, it continues to play that role even today. The internet is mostly a mesh of information transmitted through glass wires and, as you'll see later on in this section, without glass we would be unable to make the

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brains of the most advanced computers. Not bad for something that is ultimately just melted sand.

The World's First Manufactured Product

No one knows for sure who first invented glass. The earliest and most famous origin story comes from Pliny the Elder, the Roman soldier-intellectual who died in the eruption of Vesuvius in AD 79. The tale goes that many centuries earlier, Phoenician sailors had landed on a beach in what is now Israel. The Phoenicians, the great traders of the ancient era, were importing blocks of natron, an early form of soap rich in sodium (natron is why sodium's chemical symbol is Na). Before turning in for the night, the Phoenicians lit a fire on the beach, and in the absence of anywhere else to rest their pots, they perched them on some of the natron blocks. As they lit their fire and heated the blocks of natron, something extraordinary happened. Pliny writes: 'Upon its being subjected to the action of the fire, in combination with the sand of the seashore, they beheld transparent streams flowing forth of a liquid hitherto unknown: this, it is said, was the origin of glass.'[5]

The account should be taken with a pinch of salt. In practice, glassmaking had probably been discovered and rediscovered by numerous generations in numerous settings through the ages. Some have attributed it to the Syrians, others the Chinese, others the Egyptians. Some date the first innovations to the early days of pottery glazing nearly 10,000 years ago. Others put it at some point between the second and third millennia BC. Even so, apocryphal or not, Pliny's story underlines the most important lesson in the chemistry of glassmaking.

The challenge in making glass is that sand's main ingredient, silica (silicon dioxide), melts at extremely high temperatures—over 1,700°C, far higher than anything an open fire or primitive

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furnace could manage. However, add a so-called 'flux' to the mix and you can persuade the silica to melt and flow (flux) at much lower temperatures. Indeed, choose the right flux and not only will it reduce silica's effective melting temperature, it will also sop up the impurities in the glass, helping improve the final product.

For all that Pliny's story sounds like a tall tale, there are a few details which ring true, starting with the location. According to his account this all happened near the mouth of the Belus River, known these days as the Na'aman. Modern analyses show that the grains of sand found where the Na'aman empties into the Bay of Haifa are more than 80 per cent silica, with the remainder mostly consisting of fragments of shells and limestone. There are few of the impurities you often find in coastal sands.

The Phoenicians, it turns out, had happened upon the perfect sand for glassmaking. The ratio of silica to lime is just about right, so that if you added some natron to the mix and heated it enough you would end up with what is known today as soda-lime glass. Alongside the silica there was sodium carbonate (the primary ingredient in natron) for the flux and a sprinkle of lime, which helped strengthen the eventual structure.

The structure of glass is, frankly, a bit of a mess. Clear and perfect as it might appear to our eyes, down at the molecular level, glass looks more like a random ball-pit of atoms. The technical term for this jumble depends on who you're asking: for some scientists it is an 'amorphous solid', for others a 'supercooled liquid'. In theory it's both liquid and solid, though, given the way it behaves, in practice it's really the latter. Contrary to the conventional wisdom, at room temperature glass never behaves as a liquid, even an imperceptibly viscous one, even over long periods of time (though it can 'sweat' if you don't add enough lime to the mix). Those misshapen panes you sometimes see in

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old stained-glass windows, thicker at the bottom than the top, are generally not that way because the glass is slowly sagging over time. Unless the church has endured temperatures of more than 400°C, the chances are they are uneven because that's the way they were blown and solidified in the first place. Flat glass was only developed in the nineteenth century and we had to wait until the middle of the twentieth century for truly flat, thin panes.

The paradox is that, despite it being one of the very oldest human-made substances, scientists still struggle to comprehend why glass behaves the way it does. Glass seems to defy most molecular laws. As one glassmaker put it, glass is not a material; it's a state. It is more adjective than noun. Philip Anderson, who won the Nobel Prize in Physics in 1977, wrote a couple of decades later: 'The deepest and most interesting unsolved problem in solid state theory is probably the theory of the nature of glass and the glass transition.' It remains unsolved to this day.[6]

You could say something similar about much of our Material World. Our species has mastered and affected the natural environment more than any other in history yet our understanding of precisely what's *happening* to it when we experiment with it – burning this or reshaping that – remains surprisingly shallow. In much the same way as we do not fully understand the physics of glass, we don't entirely comprehend what's happening at a molecular level when concrete sets, or what's happening in the furnace when we turn quartz into metallic silicon. Mysteries abound.

Yet the eventual product, mysterious as it may be, begins with grains of sand. Much is made of the skill of the craftsmen of Murano in making extraordinary glass, but less is said about the fact that Venice happened to be perfectly sited for the raw materials needed to make that glass. The sand could come from the Lido – a nearby sandbank – and other sites along the coastline;

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soda ash could be sailed in from Egypt or Alicante; wood for the furnaces could be brought down from the lower Italian Alps; clay from Vicenza and salt from Dalmatia. Eventually the craftsmen realised that they could get even purer sands by roasting and grinding quartz pebbles – *cogoli*, as they called them – the best of which came from the bed of the River Ticino, which flows from the Swiss Alps into northern Italy. The resulting ground-down quartz was roughly 98 per cent silica. Without these sands there would have been no Venetian glass industry. For such sands are not commonplace. Which raises a question: where do we get these sands from today? Where, to put it another way, can one find the perfect grain?[7]

A Quest for the Holy Grain

Lochaline is not the most remote town in Scotland, but it still takes some getting to: a three-to-four-hour journey from Glasgow, a ferry ride and then a long, winding drive along single-lane roads through valley after valley, each more breathtaking than the last. You need a good excuse to travel somewhere like this, but as it happens I had the ideal excuse. I was on the hunt for the perfect grain of sand.

What constitutes the perfect grain of sand rather depends on who you're asking. Someone hoping to use it as an ingredient in cement or concrete will have a very different notion of perfection than someone who intends to scatter that sand on a sandpit or a volleyball court. But what I was after was nonetheless something very special indeed: one of the world's purest silica sands.

Silica sands, which is to say sands with more than 95 per cent silica, have plenty of uses. We need them to help filter our water and to make foundry moulds into which you can pour molten metals. Without silica sands the rail system would grind to a halt,

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or rather it would fail to grind to a halt, since these sands are used in modern trains' braking systems. But, most of all, silica sand is the primary ingredient in the manufacture of glass. And if you want the very clearest, finest glass, you need the very purest of all silica sands, sometimes called silver sands.

The world's most famous silver sands – at least to those who know about these things – are probably those at Fontainebleau, a forest just south of Paris. The famous glass pyramid at the Louvre is made of Fontainebleau sand. There are silver sands in Mol in Belgium, in Maastricht in the Netherlands and Lippe in Germany, as well as in Canada, the US, Brazil and other corners of the world. But while they are not exactly scarce, nor are they commonplace. Some countries have no such sands; that, indeed, was the assumption in Britain for a long time, until the discovery of Lochaline about a century ago.

My journey there was mostly conducted in heavy rain, which bombarded the windscreen as I sped past Loch Lomond and through Glen Coe, but the minute I reached the Corran ferry it suddenly stopped and gave way to warm, regenerative sunshine. I stood on the platform as the ferry pulled out across Loch Linnhe and caught a glimpse of something striking. There on the horizon was a long rift running as far as I could make out, with mountains on either side.

What I was staring at was a kind of geological scar, an ancient fault line that once split Scotland in two. This is the Great Glen Fault, a huge glacial valley that runs north-east all the way up to Inverness. At some point between 300 and 400 million years ago the land to the north detached itself from the land to the south and slid sideways, 64 miles north up the glen.

We know this because geologists have compared the rocks from one side of the fault with those from the other side. Indeed, this realisation was one of the precursors to the discovery of plate

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