WHAT A WONDERFUL WORLD

One Man's Attempt to Explain the Big Stuff

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FOREWORD

This book came about because I have an exceptional editor – Neil Belton. In fact, I am his stalker. I have pursued him all the way from Jonathan Cape to Faber. Neil has many talents. But one of those talents is that he knows what his authors are good at and what they should be writing better than they do.

My skill is that I can take complex physics and explain it to someone on a number 25 bus (or perhaps I should say someone *unfortunate enough* to be sitting next to me on a number 25 bus). But, in addition to physics, I am also interested in other things. I read a lot of fiction. I am interested in history. I like running. In fact, in 2012, I did the London Marathon (something I rarely fail to mention in the first three minutes of meeting someone).

Neil's big idea was that I combine these two things: that I use my skill at explaining complex physics in layperson's terms to explain *everything* in layperson's terms.

I was daunted. How could I possibly write about everything? Where would I even start? I began thinking about how to organise such a wide range of material logically. But I tore up outline after outline. What changed everything, however, was writing *Solar System for iPad*. I had only 9 weeks to write 120 stories about planets, moons, asteroids and comets, so I had no option but simply to dive in and learn to swim on the job. It must have worked because the App won several awards. So that is what I did. I overcame my apprehension and just dived in.

It was a struggle. Usually, when I need to know something about physics, I identify a physicist – it could be a Nobel Prize-winner – and simply phone them. There is a 95 per cent chance they will be able to answer my stupid questions immediately. And, if they cannot, they will at least make an attempt at answering them. But, with subjects I knew nothing about, such as money, sex and the human brain, it was difficult even to identify someone who might be able to answer my incredibly basic questions. And, when I did and phoned them, they were often not able to explain things at the toddler level I needed. Worse, it was sometimes as if we were speaking different languages. Often, I had to go to two, three or four people before I could find someone who could answer all my questions. And, on occasion, I could not find anyone who was able to do that. Instead, I was forced to piece together an explanation from things people I had gone to had said and from things I had read.

But Neil was right. This was the book I should have been writing. It was one that stretched me beyond my comfort zone and that, ultimately, proved to be an exhilarating and a joyful experience. I loved learning about all kinds of things I know nothing about. And I began to appreciate what a wonderful world we live in – one far more incredible than anything we could possibly have invented. Along the way, I learnt many surprising things, such as . . .

- To understand a single collaterised debt obligation squared – one of the toxic investments that sunk the world economy in 2008 – would require reading *1 billion pages* of documentation
- Slime moulds have 13 sexes (and you think you have problems finding and keeping a partner)

- You could fit the whole human race in the volume of a sugar cube
- You are ⅓ mushroom – that is, you share ⅓ of your DNA with fungi
- You age more slowly on the ground floor of a building than on the top floor
- The crucial advantage that humans had over Neanderthals was . . . *sewing*
- IBM once predicted that the global market for computers was . . . *five*
- Today your body will build about 300 billion cells – more than there are stars in our Galaxy (no wonder I get knackered doing nothing)
- Believe it or not, the Universe may be a giant hologram. *You* may be a hologram

If everything in our information-overloaded society has passed you by in a high-speed blur, my book just might bring you quickly and painlessly up to speed on how the world of the twenty-first century works. It is, after all, one man's attempt to understand everything. No, I cannot really claim that. It's one man's attempt to understand everything . . . *volume one*.

Marcus Chown, London, March 2013

I:

I AM A GALAXY

Cells

A good case can be made for our non-existence as entities.

LEWIS THOMAS

There's someone in my head and it's not me.

PINK FLOYD

I think I am me. But I am not. I am a galaxy. In fact, I am a thousand galaxies. There are more cells in my body than there are stars in a thousand Milky Ways. And, of all those myriad cells, not a single one knows who I am or cares. *I* am not even writing this. The thought was actually a bunch of brain cells – neurons – sending electrical signals down my spinal cord to another bunch of cells in the muscles of my hand.[1]

Everything I do is the result of the coordinated action of untold trillions upon trillions of cells. 'I like to think my cells work in *my* interest, that each breath they draw for *me*, but perhaps it is *they* who walk through a park in the early morning, sensing my senses, listening to my music, thinking my thoughts,' wrote American biologist Lewis Thomas.[2]

The first step on the road to discovering that each and every one of us is a super-colony of cells was the discovery of the cell itself. Credit for this goes to Dutch linen merchant Antonie van Leeuwenhoek. Aided by a tiny magnifying glass he had adapted from one used to check the fibre density of fabrics, he became the first person in history to *see* a living cell. In a letter published in April 1673 in the *Philosophical Transactions* of the Royal Society of London, van Leeuwenhoek wrote, 'I have observ'd taking some blood out of my hand that it consists of small round globuls.'

The term 'cell' had actually been coined two decades earlier by the English scientist Robert Hooke. In 1655, he had examined plant tissue and noticed dead compartments stacked together. However, neither he nor van Leeuwenhoek realised that cells are the Lego bricks of life. But that is what they are. A cell is the 'biological atom'. There is no life – as far as we know – *except cellular life*.

Prokaryotes: a protected micro-universe

The first evidence of cells comes from fossils about 3.5 billion years old. But there is more tentative evidence, from about 3.8 billion years ago, in the shape of telltale chemical imbalances in rocks that are characteristic of living things. The first cells, known as prokaryotes, were essentially just tiny transparent bags of gloop less than a thousandth of a millimetre across. The bag, by concentrating stuff inside, speeded up key chemical reactions such as those that generate energy. It also protected proteins and other fragile products of those reactions from toxic substances such as acids and salt in the environment. The bag of gloop was an island haven in an ocean of disorder and chaos, a protected micro-universe where order and complexity might safely grow.

The complexity of such cells was in large part due to the proteins – megamolecules assembled from amino-acid building blocks and made of millions of atoms. Depending on their shape and chemical properties, these Swiss-army-knife molecules can carry out a myriad tasks, from speeding up chemical reactions to acting as cellular scaffolding to flexing like coiled springs to power the movement of cells. Even a simple bacterium possesses about four thousand different proteins, though some proteins, such as those needed for reproduction, are assembled, or expressed, only intermittently. The structure of these proteins is encoded by deoxyribonucleic acid, or DNA, a double-helical molecule floating freely as a loop in the chemical soup, or cytoplasm, inside a cell.

Cellular structure is beautifully intricate. First, there is the bag, or membrane. This is made of fatty acids, molecules that are characterised by having a water-loving end and a water-hating end. When such lipids come together in large numbers – typically a billion – they spontaneously self-assemble into two layers, with their water-hating ends on the interior and their water-loving ends on the outside.

The lipid layers that enclose a cell are not a passive barrier. Far from it. This double skin regulates the molecules coming in and going out of the cell. Imagine the cell as an ancient city surrounded by a wall. In the same way that small creatures such as mice can pass easily back and forth through the city wall, small molecules can pass unhindered in and out of the cell membrane. And, just as bigger creatures such as people are admitted only through gates in a city wall, the passage of big molecules is regulated by 'gates' in the cell membrane. For instance, there are proteins shaped like hollow tubes spanning the width of the membrane through which bigger molecules can tunnel into and tunnel out of the cell. And there are transporter proteins whose job is to shuttle bigger molecules physically from one side of the membrane to the other.

The molecules that come in to the cell are those needed for energy and to make proteins and to provide information about the outside world. For instance, an abundance in the surrounding environment of molecules necessary for building new cells might trigger a cell to reproduce.[3] On the other hand, a shortage of water molecules coming across the membrane might warn a cell that it is in danger of drying out. This might trigger a cascade of chemical reactions inside the cell, ultimately causing a stretch of DNA to be copied repeatedly into molecules called ribonucleic acid, or RNA. These find their way to ribosomes, nanomachines that use the RNA templates to make proteins that might be components of a mucus that will protect the cell from dehydration.[4] Too big to pass through the cell membrane, the proteins flooding out through the cytoplasm in their millions are packaged into membrane sacs, or vesicles, which fuse with the cell membrane. The membrane can then open up, without rupturing and losing its structural integrity, and cast them into the outside world.

But cells, in addition responding to molecules in their environment, also respond to molecules from *other cells*. Even the simplest and most ancient prokaryotes cooperated with each other, which is revealed by fossils of large microbial communities known as stromatolites. Living stromatolites can still be found today – for instance, in shallow tropical waters off the western coast of Australia – but the oldest of these fossil communities is about 3.5 billion years old.

At the same time that a cell makes proteins to protect itself from environmental changes, it might produce proteins that warn others of its kind to do the same. Such chemical signalling is crucial to the survival of simple prokaryotes, which often live in huge colonies known as biofilms, quite possibly the first organised structures to appear on Earth. The cells on the inside of such a biofilm might secrete a sugary protein that sticks their membranes to the membrane of other cells, whereas those on the outside of the film might produce proteins that help protect them from environmental toxins. Some cells will even kill themselves in order to yield up precious nitrogen for the good of their companions. This kind of cooperation, with cells within a group differentiating to carry out different tasks, is reminiscent of the cells in our bodies. It hints at how such cellular super-cooperation might have got started billions of years ago.

There are limits on the size and complexity of prokaryotes. For one thing, the proteins assembled, or expressed, by their DNA can travel only by drifting slowly, or diffusing, across a cell. Beyond a certain size, a prokaryote is therefore suicidally slow in reacting to environmental dangers. This problem has been solved by rare prokaryotes such as *Thiomargarita namibiensis*, discovered only in 1997. The giant sulphur bacterium, which is about 0.75 millimetres across and easily visible to the naked eye, possesses not one loop of DNA but *thousands*, spread evenly throughout its cytoplasm. This means that proteins expressed by local strands of DNA, even if they diffuse slowly, can still get to all parts of the cell rapidly.

But there is another serious problem that keeps prokaryotes small. The bigger one of them grows the more energy it needs. If it were to use the strategy of *T. namibiensis*, however, an increasing proportion of that energy would be needed for manipulating large quantities of DNA. Since this would be at the expense of any other cellular processes, the road to increased complexity is well and truly blocked.

But there is another way to grow big: take up cannibalism.

Eukaryotes: cities in bags

About 1.8 billion years ago, a prokaryote swallowed another prokaryote. Prokaryotes actually include bacteria and more exotic archaea bacteria, microorganisms that survive in extreme environments such as boiling sulphur springs and so were probably among the first life forms on Earth.[5] What actually happened 1.8 billion years ago was that an *archaeobacterium swallowed a bacterium*.

Such an event must have occurred innumerable times before. But, in all cases, the bacterium was either devoured or spat out. This time, for some unknown reason, the bacterium survived. More than that. *It thrived*. There was some mutual benefit for the swallower and swallowee. The latter found a protective environment, safe from the hostile outside world, and the former a new power source.

The evidence that something like this did indeed happen was gathered by the American biologist Lynn Margulis (the first wife of TV astronomer Carl Sagan). And the evidence is still around us today. The energy-generating mitochondria inside the eukaryotic cells of all animals are not only the same size as free-living bacteria but they *look like them too*.[6] Even more striking, they have their own DNA, which is separate and distinct from the DNA of the whole cell, and fashioned into a loop exactly as in prokaryotes.

In fact eukaryotes may have hundreds, or even thousands, of such mitochondria. These are self-contained power stations, furiously reacting hydrogen from food with oxygen to make life's mobile power packs, adenosine triphosphate, or ATP.[7] 'My mitochondria comprise a very large proportion of me,' wrote American biologist Lewis Thomas. 'I suppose there is almost as much of them in sheer dry weight as there is of the rest of me. Looked at this way, I could be taken for a very large, motile colony of respiring bacteria.'[8]

With a cell's mitochondria working semi-autonomously in this way, it is no longer necessary for it to devote so much of its DNA to the task of generating energy. The DNA is free to encode other things, other protein nanomachinery. Consequently, when cells gained mitochondria 1.8 billion years ago, they were suddenly free to grow a whole lot bigger and more complex.

A large eukaryote compared with a typical prokaryote is like a cat beside a flea. Such a mega-cell might contain hundreds, even thousands, of membrane-enshrouded bags. These organelles divvy up the chores of the cell, functioning as the equivalent of factories, post-office sorting offices and other specialist buildings in a modern-day city.

Lysosomes, for instance, are the garbage-disposal units of the cell. They break down molecules such as proteins into their building blocks so they can be used again. The reason the lettuce in your burger wilts is that heat from the beef breaks down the lysosome membranes of the lettuce cells. This unleashes enzymes, which devour the lettuce. Other organelles include the rough endoplasmic reticulum, which acts like a cellular DHL office. Dotted with ribosomes, it translates RNA arriving from the nucleus into proteins destined for foreign parts beyond the cell. Yet another organelle is the Golgi apparatus, which acts like a packaging centre. It can modify proteins, wrapping them, for instance, in a sugar coating that absorbs water. Such proteins can be used to make the surfaces of blood cells slimy so they can move about more easily.[9]

In fact, a eukaryotic cell is less like a single organism than a colony of organisms, each of which long ago lost its ability to survive alone. 'For the first half of geological time our ancestors were bacteria,' says Richard Dawkins. 'Most creatures still are bacteria, and each one of our trillions of cells is a colony of bacteria.' And all of this has come about by chance. 'The mitochondrion that first entered another cell was not thinking about the future benefits of cooperation and integration,' says Stephen Jay Gould. 'It was merely trying to make its own living in a tough Darwinian world.'[10]

The organelles are subservient to the cell's nucleus, which contains its DNA and orchestrates pretty much all cellular activity. The English botanist Robert Brown recognised the nucleus as a common feature of complex cells in 1833.[11] Enclosed in a double membrane, the nucleus is reminiscent of a walled castle inside the walled city of the cell. The membrane controls the passage of molecules into the nucleus and the passage of proteins expressed by the DNA out of the nucleus.

The presence of a nucleus is one of the defining features of a eukaryote, along with the presence of a plethora of organelles. A prokaryote has neither a nucleus nor organelles. In fact, the very word *prokaryote* means 'before kernel, or nucleus', while *eukaryote* means 'true nucleus'. Very probably, a nucleus is a necessity in a cell as complex as a eukaryote because of the need to protect the precious DNA from the frenzied activity going on in every corner.[12]

In addition to having a nucleus and a large number of organelles, a eukaryote contrasts with a prokaryote in having a cytoskeleton. Proteins such as tubulin form long scaffolding poles that criss-cross the cell. Such microtubules stiffen the soft bag of the cell, giving it a shape. They also anchor organelles to the membrane. This ensures that they are arranged in a similar way in all eukaryotes much as internal organs are arranged in a similar way in all humans. But, in addition to providing internal scaffolding, microtubules act as an internal rail network that can rapidly transport material about the cell. They do this by growing at one end and disintegrating at the other, so, bizarrely, *it is the track rather than the train that provides the motive power*. Newly made proteins, enclosed in bags, or vesicles, simply hop on a convenient microtubule and are instantly speeded off to a far-away destination within the cell.

The cellular rail network enables a eukaryote to overcome one of the biggest obstacles preventing a prokaryote becoming big: getting stuff around the cell. A eukaryote, rather than having to wait for proteins to diffuse slowly through the cytoplasm, speeds them around on its rapid transit network.

But eukaryotes, despite being an enormous advance over prokaryotes, also have their limits. Orchestrating organelles is a complex activity. If a cell contained more than a few thousand of them, such orchestration would be beyond the capability of a nucleus. Eukaryotes, like prokaryotes, are a biological dead end. The way to increasing complexity lies in another direction – in cooperation on an unprecedented scale.

Multicellular organisms

From the moment they arose, eukaryotes almost certainly cooperated with each other in increasingly sophisticated ways. But, about 800 million years ago, they crossed a critical threshold. Nature had put together colonies of symbiotic prokaryotes to make eukaryotes. Now it repeated the trick. It put together colonies of symbiotic eukaryotes to make multicellular organisms.

The fact that life on Earth spent about 3 billion years at the single-cell stage before it took the step to the multicellular stage is probably telling us that the step is a difficult one. This has implications for the prospects of finding extraterrestrial life.

Despite fifty years of searching, astronomers have seen no sign of intelligence elsewhere in our Galaxy. One possibility is that life is common in the Milky Way but only in the form of single-celled microorganisms.

Humans – as well as animals, plants and fungi – are all multicellular organisms. Each of us is a colony of about 100 million million cells. They come in about 230 different types, ranging from brain cells and blood cells to muscle cells and sex cells, and all are enclosed in a bag made of skin cells, no less a container than the membrane of a single cell.

Each cell has its own copy of the same DNA (apart from blood cells in their mature form, which are so utilitarian they lack even a nucleus). But whether a cell becomes a kidney cell or a pancreatic cell or a skin cell depends on the particular section of the DNA that is read, or expressed. This, in turn, depends on regulatory genes – themselves stretches of DNA – which can turn off and turn on the reading of DNA, depending on things such as the concentration of a particular chemical in the locality.

Each of the 100 million million cells that makes up a human being is a micro-world as complex as a major city, buzzing with the ceaseless activity of billions of nanomachines. It has storehouses, workshops, administrative centres and streets heaving with traffic. 'Power plants generate the cell's energy,' says American journalist Peter Gwynne. 'Factories produce proteins, vital units of chemical commerce. Complex transportation systems guide specific chemicals from point to point within the cell and beyond. Sentries at the barricades control the export and import markets, and monitor the outside world for signs of danger. Disciplined biological armies stand ready to grapple with invaders. A centralised genetic government maintains order.'[13]

And all of this is going on every moment of every day of our lives while we remain utterly oblivious to it. In the words of biologist and writer Adam Rutherford, 'Each movement, every heartbeat, thought, and emotion you've ever had, every feeling of love or hatred, boredom, excitement, pain, frustration or joy, every time you've ever been drunk and then hungover, every bruise, sneeze, itch or snotty nose, every single thing you've ever heard, seen, smelt or tasted *is your cells communicating with each other and the rest of the Universe*.'[14]

We all start our lives as a single cell when a sperm, the smallest cell in the body, fuses with an ovum, the biggest cell in the body and one actually visible to the naked eye. Every human in fact spends about half an hour as a single cell before it splits into two. This is a phenomenal process in itself. In a mere thirty minutes, not only must a cell make a copy of its DNA – a process that, for speed, occurs simultaneously at multiple sites on the DNA – but it must construct something like 10 billion complex proteins. This is more than *100,000 a second*.

Within sixty minutes, the two cells split into four, then later eight, and so on. After several divisions, chemical differences across the developing embryo cause the cells to differentiate. It is a process that culminates in cells 'knowing' they have to be kidney cells or brain cells or skin cells. Over years, a single cell becomes a galaxy of cells – or, rather, a *thousand galaxies of cells*.

Hardly any of the cells in your body – apart from brain cells – are permanent. The cells lining the wall of the stomach are bathed in hydrochloric acid strong enough to dissolve a razor blade, so must be remade constantly. You get a new stomach lining every three or four days. Blood cells last longer but even they self-destruct after about four months. It is fair to say that you are pretty much a new person every seven years, something that maybe explains the seven-year itch. You look at your partner and suddenly think, 'That's not the person I got together with!'

The cells of your body die in such prodigious numbers that, simply to replace them, you must build about 300 billion new cells every day. That is more cells than there are stars in our Galaxy. No wonder it can be tiring doing nothing.

Aliens

There may be an astronomical number of cells in your body. But they are not able to carry out all the functions necessary for your survival. Not without assistance from legions of alien cells such as prokaryotes, fungi and single-celled animals called protozoans.[15] In your stomach, for instance, hundreds of species of bacteria work constantly to extract nutrients from your food. If some of these 'good' bacteria are inadvertently killed by antibiotics, the result can be an affliction such as diarrhoea.

The alien bacteria protect you from illness by filling niches in your body that otherwise might be filled by disease-causing pathogens. The Human Microbiome Project, a five-year study funded by the US government, presented its findings in 2012. It found that the nasal passages of about 29 per cent of people contain *Staphylococcus aureus* – better known as the MRSA superbug. Since such people suffer no ill effects, the implication is that in healthy people the bugs act as good bacteria, keeping harmful pathogens at bay.

Remarkably, the Human Microbiome Project found that there are more than 10,000 species of alien cells in your body – 40 times the number of cell types that actually belong to you. You are only 2.5 per cent human. In fact, about 5 million bacteria call every square centimetre of your skin home. The most densely populated regions are your ears, the back of the neck, the sides of the nose and your belly button. What all these alien bacteria are doing is a mystery. The Human Microbiome Project found that 77 per cent of the species in your nose, for instance, have completely unknown functions.

The sheer number of alien bacteria in your body might actually underrate their importance. The Human Microbiome Project found that microorganisms that inhabit your body have a total of at least 8 million genes, each of which codes for a protein with a specific purpose. By contrast, the human genome contains a mere 23,000 genes.[16] Consequently, there are about 400 times as many microbial genes exerting their effect on your body as human genes. In a sense, you are not even as much as 2.5 per cent human – you are merely 0.25 per cent human.

Since the alien cells in your body are largely prokaryotes, which are much smaller than eukaryotes, they add up to a few kilograms or a mere 1–3 per cent of your mass. They are not encoded by your DNA but infected you after birth, via your mother's milk or directly from the environment. They were pretty much all in place by the time you were three years old. It is fair to say that we are born 100 per cent human but die 97.5 per cent alien.

The biological event horizon

Every cell is born from another cell. '*Omnis cellula e cellula*', as François-Vincent Raspall first recognised in 1825. Consequently, every cell in our body – every cell on the Earth – can trace its ancestry in an unbroken line back to the very first cell, which appeared about 4 billion years ago. The first cell is generally referred to as the last universal common ancestor, or LUCA. Nobody knows how exactly it came about. Undoubtedly, there was a vast amount of experimentation – a huge amount of pre-evolution – before nature hit on the design.

Mistakes, or mutations, in genes accumulate at a steady rate over time. So, if one species has twice as many mutations of a particular gene as a second species, we can say it split from a common ancestor twice as far back. This is how the tree of life, first envisaged by Charles Darwin, is constructed. However, bacteria have an inconvenient habit of swapping DNA as well as passing DNA to their descendants. This means that, in the vicinity of LUCA, the tree of life is less a tree and more like an impenetrable thicket.

In physics, scientists talk of the 'event horizon' of a black hole – the point of no return for infalling matter. It cloaks the black hole so that nothing can be seen of its interior. Similarly, biologists talk of the biological event horizon beyond which nothing can be known. There, unfortunately, lies LUCA.

Since the time of LUCA, the Earth, despite dabbling in multicellularity, has been a bacterial world. There are believed to be something like 10,000 billion billion billion bacteria on our planet. That is a billion times more bacteria than there are stars in the observable Universe. But this might not give a true picture of terrestrial biology. Consider viruses. 'We live in a dancing matrix of viruses,' wrote Lewis Thomas. 'They dart, rather like bees, from organism to organism, from plant to insect to mammal to me and back again, and into the sea, tugging along pieces of this genome, strings of genes from that, translating grafts of DNA, passing around heredity as though at a great party.'[17] Incapable of reproducing without hijacking the machinery of cells, viruses are generally not considered to be precursors of cellular life. But who knows?

8:

THANK GOODNESS OPPOSITES ATTRACT

Electricity

We believe that electricity exists because the electric company keeps sending us bills for it, but we cannot figure out how it travels inside wires.

DAVE BARRY

Is it a fact – or have I dreamt it – that, by means of electricity, the world of matter has become a great nerve, vibrating thousands of miles in a breathless point of time?

NATHANIEL HAWTHORNE, *The House of the Seven Gables* (1851)

A thin metal wire comes into your home and something *invisible* travels down it. The *something* not only has the *oomph* to spin the tumbler of a washing machine but to light every room in your home – and in winter even heat your home as well. Not only your home but millions of other homes. *Billions* even. Everyone knows that electricity powers the planet. But how in the world does it do it?

Here's an explanation. It requires a little background. Imagine there is a force that behaves like gravity but differs from gravity in two key respects.[1] First, instead of separate chunks of matter always attracting each other in the way that the Sun and Earth do, there are *two* types of matter that experience the force differently. Call them Type 1 and Type 2, or A and B, or positive and negative. It does not matter. The key thing is that *unlikes* attract with the force while *likes* repel with the same force.

A bunch of positives therefore repel and flee from each other in all directions and a bunch of negatives does exactly the same. However, with an evenly mixed bunch of positives and negatives, something quite different happens. The opposite pieces pull each other together and the like pieces drive each other apart. But, because the opposing forces are equal and opposite, there is a perfect balance.

It follows that if there are two bodies, each of which is an equal mixture of negatives and positives, they will neither attract nor repel each other.

A force that behaves like this does indeed exist. It is called the *electric force*. And ordinary matter – the stuff of which you and me and the world around us is made – turns out to be an even mixture of positively *charged* protons and negatively *charged* electrons. (Protons are confined to the core, or nucleus, of each atom, whereas electrons orbit the nucleus.) The balance of attraction and repulsion is so perfect that, when you stand near someone else, neither of you feels the slightest force. In fact, in everyday life, there is very little hint that the electric force exists at all.

A force that can be both attractive and repulsive but which, in normal circumstances, is cancelled out perfectly probably seems dull and unremarkable. But, remember, the electric force differs from gravity in not one but *two* respects. While the first difference ensures that the force is pretty much always nullified, the second difference is at the very root of the force's extraordinary ability to power the modern world. The electric force is *stronger* than gravity. But not by a factor of 10. Or of 100. Or even a million. No, the electric force is stronger than the force of gravity by a factor of *10,000 billion billion billion billion*.[2]

To get some idea of what this enormous number means, imagine a mosquito buzzing in a jar. Say, by some wizardry, it is possible to remove all the negative electrons from the atoms of the mosquito so that all that are left behind are the positive atomic nuclei.[3] These will, of course, repel each other. The mosquito will explode. The question is: with how much energy will the mosquito explode?

(a) The energy of a sparkler?
(b) The energy of a stick of dynamite?

(c) The energy of a 1-megatonne H-bomb?
(d) The energy of a global mass extinction?

Perhaps you think the answer is (b) a stick of dynamite, or maybe (c) a 1 megatonne H-bomb? If you think (c), you are at least on the right track. A hydrogen bomb is a useful comparison. But not a *single* hydrogen bomb. *A million billion 1-megatonne H-bombs*. The mosquito will explode with an energy equivalent to the city-sized asteroid that slammed into the Earth 65 million years ago and wiped out the dinosaurs. The answer is (d). The mosquito will explode with the energy of a *global mass extinction*. Were it not for the fact that the mind-bogglingly huge electric force – 10,000 billion billion billion billion times stronger than gravity – is invariably cancelled out, each and every mosquito on Earth would be a potential world-destroyer. Thank goodness that in physics, as in life, opposites attract.

Now perhaps it is possible to appreciate the potential of the electric force for energising the world.

Removing all the electrons from a mosquito – if it were possible – would create a dramatic charge imbalance and unleash a truly extraordinary amount of electric energy.[4] It follows that creating even a modest charge imbalance might unleash a significant amount of electric energy. This is what happens in a thunderstorm. Here, a charge imbalance builds up between a cloud and the ground (or, more commonly, between one cloud and another). Specifically, the underside of a cloud builds up a negative charge at the expense of the ground, which becomes positively charged. Eventually, the electric force between the cloud and the ground becomes so immensely strong that it is able to rip the outer electrons from the atoms in the air between.

This breakdown of the air sends an avalanche of electrons – typically, 100 billion billion of them – surging down to the ground to cancel out the charge imbalance. In short, it creates a lightning bolt.

A flow of electrons is called an electric current.[5] Typically, in the case of a lightning bolt, the current is about 10,000 amps, though it can be as high as a few hundred thousand amps (by comparison, many household electrical appliances use less than 10 amps). For just a tenth of a second or so, the current surges down a channel the width of a pencil.[6] The electrons that compose it slam into air atoms, like a myriad tiny ball bearings, transferring energy to their still-bound electrons. The air atoms gain so much energy that the temperature can soar to about 50,000 °C – almost 10 times hotter than the surface of the Sun. It is the supersonic expansion of this blisteringly hot air on either side of the lightning channel that creates the clap of thunder. And it is the atomic electrons, shedding their excess energy as photons, that *light up* the lightning bolt.

Lightning demonstrates some key properties of electricity. One is that, if a charge imbalance is created, the electric force is presented with an opportunity to unleash a large amount of energy.[7] Another is that electrical energy can be transferred *across a distance* by an electric current. In a lightning bolt, the distance is typically a couple of kilometres. However, the longest recorded streak of lightning, observed near Dallas, Texas, was almost 200 kilometres long. The ability to transfer energy across a distance by an electric current has been of huge significance in creating the modern technological world.

Lastly, of course, lightning demonstrates that, by means of an electric current, it is possible to change electrical energy into other forms of energy – specifically, heat and light. The 'killer app', responsible for kick-starting the electrical revolution of the late nineteenth century, was in fact the light bulb. The electrical pioneers were not thinking about putting electricity into the home or even electrical appliances in the home. They were thinking about putting *light in the home*. 'The light bulb is what wired the world,' says Jeff Bezos, founder of Amazon.com.

Just as a current in lightning transfers energy to the air – heating and lighting it up – a current in a light bulb transfers energy to a filament – heating and lighting it up. The clever bit – perfected, though not invented, by Thomas Edison – is putting a filament in an oxygen-free glass bulb so that it glows *without burning away*.[8]

But although lightning demonstrates some key properties of electricity, building up a huge charge imbalance and waiting for the air to break down catastrophically is hardly a practical way to generate an electric current. Fortunately, there is a more convenient and controlled way. To understand it, however, it is first necessary to appreciate how exactly the electric force of an electric charge reaches out across space and influences other charges.

The electric force field

If you rub a balloon against a nylon sweater, loose electrons get transferred from one to the other. It does not matter which way they go – and, in fact, it is not entirely clear. The point is that both the balloon and sweater become electrically charged.[9] If you now bring the charged-up balloon close to a small scrap of paper, the scrap will leap through the air, yanked by the electric force, and glue itself to the balloon.[10] Somehow, the electric force of the balloon has reached out through the air and grabbed the scrap of paper.

Physicists say that extending out through space from an electric charge is an invisible electric *force field*, rather like a *Star Trek* tractor beam. When the paper finds itself in the field, it experiences a force towards the charge.[11]

The field of force around a charged balloon is feeble but between a storm cloud and another cloud or between a cloud and the ground it can be enormous. And it is this field that eventually becomes so irresistibly strong that it tears electrons from the very atoms of the air, creating the electron avalanche of a lightning bolt. In fact, the field in a thunderstorm can be strong enough to be *felt*, prickling the skin and even making hair stand on end. Mind you, if you experience either of these sensations, throw yourself flat to the ground. A lightning strike is imminent and your name is written on it.

The magnetic force field

But there is more to the electric field than an invisible force field that extends outwards from an electric charge (pulling in unlike charges and pushing away like charges). This merely describes the force surrounding a *static* charge. If the charge is *moving* relative to a second charge, a new force puts in an appearance. The second charge, in addition to the electric force, experiences a *magnetic force*.

The magnetic force field is easier to imagine than an electric force field. After all, if you have a bar magnet and a nail and bring them together, you can actually *feel* the invisible tractor beam of the magnetic field of the magnet clamping onto the nail. In fact, it was seeing the needle of a magnetic compass respond to the Earth's magnetic field that blew the mind of Albert Einstein, aged four or five, switching him on to science and teaching him a lesson about nature that he never forgot: there is 'something behind things, something deeply hidden'.[12]

The fact that a magnetic field is caused by a *moving electric charge* helps explain the origin of the magnetic field of permanent magnets. Every material, including the flesh and blood of which you are made, consists of countless charged electrons, not only moving in orbit around the nuclei of atoms but actually behaving like tiny spinning tops themselves. This means every atom and every electron is like a tiny magnet. In most materials, all the countless mini-magnets are orientated randomly and so, overall, their magnetic fields cancel out. However, in some materials, this cancellation is not perfect. Such materials are permanent magnets.

The fact that a moving electric charge creates a magnetic field was first noticed in 1820 by Danish physicist Hans Christian Ørsted. He saw that the needle of a magnetic compass was deflected when he brought it close to a conducting wire carrying an electric current. A current, by definition, is electric charge in motion, and electric charge in motion obviously has a changing electric field. What Ørsted realised was that *a changing electric field creates a magnetic field*.

Bring two magnets together and feel the powerful force between them.[13] As Ørsted discovered, a current-carrying coil of wire, with its changing electric field, *is* a magnet. Bring it together with a permanent magnet and there will be a force between the two, just as there would be between two permanent magnets. Arrange the coil and the magnet in the right way – and this takes some ingenuity – and the force will cause the coil of wire to *spin*. *Voilà*. You have created an electric motor.

The reason a magnetic field can spin something is that it has what physicists call curl. Whereas an electric field extends radially outwards from a charge, a magnetic field – for instance, one created by a current-carrying wire – swirls around like a miniature tornado of force.

With the aid of an electric motor, it is possible to do a lot more with an electric current than merely create heat and light. It is possible to *move* things. In the motor of an electrical appliance, the changing electric field of an electric current generates a magnetic field of the force that propels a spindle. It is possible to drive everything from washing machines to automatic doors to electric cars and trains. And this is all down to the simple fact that a *changing electric field creates a magnetic field*.

Of course, it goes without saying that the prerequisite for running an electric motor is an electric current. Nature can create one – fleetingly and chaotically – in a lightning bolt. But how is it possible to create an electric current in a practical and controlled way? The answer is by exploiting another property of electric and magnetic fields. It was first noticed in 1831 by English physicist Michael Faraday. Faraday was the father of our electrical power system. 'Even if I could be Shakespeare I think that I should still choose to be Faraday,'[14] wrote Aldous Huxley, author of *Brave New World*. And, famously, when asked by William Gladstone, Chancellor of the British Exchequer, 'What is the practical use of electricity?', Faraday replied, 'Why, sir, there is every probability that you will soon be able to tax it.'

Faraday noticed that, when he moved a magnet in the vicinity of a coil of conducting wire, an electric current flowed fleetingly in the coil.[15] A current is a flow of charges, and charges are propelled by an electric field. What Faraday had noticed was that *a changing magnetic field creates an electric field*.

There is a pleasing symmetry between electric and magnetic fields. Not only does a changing electric field create a magnetic field but a changing magnetic field creates an electric field. Spin a coil of wire in the magnetic field of a permanent magnet. Arrange the coil and magnet in the right way – and this also takes some ingenuity – and an electric field will be created in the coil, which will drive a current. *Voilà*. You have created an electric generator.

At a power station, a coil of wire is spun in the force field of a magnet. The thing doing the spinning could be wind or water, or steam from water heated by coal or oil or nuclear power.[16] The key thing is that the spinning coil cuts through the magnetic field. In other words, the magnetic field through the coil *changes*. And the changing magnetic field creates an electric field, which pushes electrons around the coil. It creates a current. The same current that surges out of the power station down a cable and powers your home.

In practice, the current goes in and out of each home *in the same cable*. The current arrives from the power station in the live wire and returns to the power station in the neutral wire, thus completing the circuit.[17] There is a twist, however. Although the statement above is basically true, power stations do not generate current that flows in one direction only. Instead of direct current, or DC, they generate alternating current, or AC, which sloshes back and forth, rapidly changing its direction. The reason for this is to overcome a major problem with the long-distance transmission of electricity.

Alternating current

Think of an electric current flowing from a power station like a stream flowing down a hillside to a valley bottom. If you were to intercept the stream near the top of the hill, you would be able to exploit the long drop of the water to the valley bottom to power a piece of machinery such as a water wheel. However, if you were to intercept the stream close to the valley bottom, there would be very little drop left that could be exploited. And this is also the problem with an electric current flowing from a power station. The further away a home, the less energy can be extracted from the flow of electrons. While those close to the power station might be able to light their homes with a multitude of bright light bulbs, those far away will have to make do with the faintest of glimmers from a single light bulb.

The amount of energy a current can deliver is characterised by its voltage, which is analogous to the height of that stream above the valley bottom. In the UK, domestic appliances work on 240 volts (110 volts in the US). This would seem to imply that a power station would have to generate electricity at near 240 volts. But, of course, if it did, those living far away might have to make do with 100 volts, or 10, or even a measly 1 volt. In New York in the 1880s, the only way Edison could overcome this Achilles heel of electric power transmission was to build a power station about every 2.5 kilometres. Although this is just about doable, it is clearly an unworkable solution for distributing electrical power nationally.

The solution to the transmission problem, pioneered by Nikola Tesla and others, is to generate the electrical power not at 240 volts but at a voltage about *a thousand* times greater. In the UK's

National Grid, electricity is transmitted over long distances at 110,000 volts or higher.[18] This means that, if the electrons lose energy travelling down the wire from a power station – and they inevitably do, banging into atoms and losing energy as heat – the voltage drop is hardly noticeable compared with 110,000 volts. Consequently, it is possible to transmit electricity over huge distances, and power stations do not have to be near homes. The problem is that 110,000 volts is too enormous for household appliances. Somewhere between a power station and people's homes, the voltage must reduced, or stepped down. This is not possible with a direct current. But it is possible with an *alternating current*.

An alternating current switches direction rapidly, commonly between 50 and 60 times a second. Think of the electrons in a wire as sloshing back and forth like waves on a sea shore. And, since an alternating current is ultimately made of countless *moving* electrons exactly like a direct current, it can carry energy as efficiently as its uni-directional cousin.[19] Furthermore, it is possible to design both a generator to *create* alternating current and a motor to *run on* alternating current. There remains only the problem of stepping down an AC current from 110,000 volts to the 240 volts required domestically. But this can be done with a transformer.

In a transformer, a current changing in one coil of wire – that is, an alternating current – causes a changing magnetic field in a second coil. This, in turn, creates a changing electric field, which drives a changing current in the second coil. If the second coil has fewer *turns* than the first, then the voltage *goes down*.

So there you have it: our electrical power system in a nutshell.

Electricity, magnetism and light

But electricity and magnetism have some more tricks up their sleeve. Recall that, if an electric charge is moving relative to you, you see not only an electric field *but a magnetic field*. However, if you travel alongside the charge, so that it is not moving relative to you, you see no magnetic field. And this is not all. If a magnet is moving relative to you, you see not only a magnetic field *but an electric field*. But, if you travel alongside the magnet, you see only a magnetic field.

How is it possible that, from one perspective, there is a magnetic field and, from another, no magnetic field? How is it possible that, from one perspective, there is an electric field and, from another, no electric field? There is only one way it can be possible: if magnetic fields and electric fields are *not fundamental things at all*.

As Einstein realised in 1905, an electric field and a magnetic field, just like space and time, are simply different facets of the same thing – an electromagnetic field. How much of each facet you see depends on your speed relative to the source of the electromagnetic field. This is why what one person sees as an electric field someone else sees as an electric field *and a magnetic field*. This is why what one person sees as a magnetic field someone else sees as a magnetic field *and an electric field*. No wonder there is a pleasing symmetry between the behaviour of electric and magnetic fields. How can there not be? They are essentially the *same* thing.

But there is yet more. In 1863, the Scottish physicist James Clerk Maxwell, in a scientific tour de force, distilled all known electrical and magnetic phenomena into a single neat set of equations.[20] Studying those equations, he noticed something remarkable. It appeared possible for a ripple to propagate through the electric and magnetic fields just like a wave on a lake. Not only was the ripple self-sustaining but it travelled at a very particular speed: *the speed of light*.

Maxwell had discovered a surprising connection between electricity and magnetism *and light*. Light, it turns out, is a wave of electromagnetism – an electromagnetic wave.[21] And there is more. Maxwell's equations reveal that it is possible to have electromagnetic waves that oscillate both more rapidly and more sluggishly than visible light. In 1888, their existence was proved by the German physicist Heinrich Hertz. With the aid of a spark, he transmitted an electromagnetic wave. The invisible-to-the-naked-eye radio wave crossed his laboratory and induced a measurable current in a coil of wire. It was an epochal, world-changing moment. All radio and television communications around the world began with that one triumphant demonstration. Our connected modern world was born that day. 'From a long view of the history of mankind, seen from, say ten thousand years from now, there can be little doubt that the most significant event of the nineteenth century will be judged as Maxwell's discovery of the laws of electrodynamics,' said American Nobel Prizewinner Richard Feynman.[22]

Electricity and the realm of the atom

Electricity opened up technological possibilities that were unimaginable to earlier generations. Not only was it possible to transmit a signal around the globe so that one person could talk to another without any material connection existing between them but it was possible to run huge extended power systems. In the evocative words of Feynman, 'Ten thousand engines in ten thousand places running the machines of industries and homes – all turning because of the knowledge of electromagnetism.'[23]

But, hand in hand with the harnessing of electricity came a dawning realisation that electricity is of central importance in nature. We live in an electrical world. Nobody had realised this before because, in pretty much all everyday circumstances, the enormous electric forces are perfectly balanced and so nullified. This is not the case, however, in the realm of the atom, the building block of all matter. There charge imbalances are ubiquitous.

As the joke goes . . .

Two atoms are walking down the street when they collide. One says to the other, 'Are you all right?'

'No, I lost an electron.'

'Are you sure?'

'Yeah, I'm positive.'

In a piece of matter with only a few atoms, there will usually not be an equal number of positive and negative charges. And, even if there are, there might still be large electrical forces. This is because the negative charge of one piece of matter might be closer to the positive charge of another piece of matter than its negative charge. Since the electrical force weakens with distance, attraction will win out over repulsion. Thus it is possible for two small pieces of matter to attract each other fiercely even if neither has a net charge.

Atoms, it turns out, are totally dominated by the immensely strong electric force. The glue that holds them together, and sticks them to other atoms to make molecules, is the electrical force. All chemistry, which involves the rearrangement of electrons in atoms, is electrical. The attraction of the electrical force not only holds the atoms in the molecules of your body together but the repulsion between the electrons on the outside of those molecules keeps you rigid, preventing the Earth's gravity from crushing you flat. And your cells have learned how to tap the energy of the electric force. Electrons from food create electric fields across cell walls that drive the creation of power-pack molecules such as adenosine triphosphate, or ATP. And electrons help to store and carry our very thoughts.[24]

Biology runs on electricity. We are electrical beings. We are as animated by the electrical force as much as a battery-powered toy is animated by the electrical force. Which explains why electricity is not only miraculous but *dangerous*. 'My nephew tried to stick a penny into a plug,' said American comedian Tim Allen. 'Whoever said a penny doesn't go far didn't see him shoot across that floor.'