Educating Newton
Rediscovering Science

Colin M. Frayn
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For my family
Introduction

At the entrance to the chapel of Trinity College, Cambridge, stands a life-size marble statue facing eastwards towards the high altar. It depicts an elderly man, richly draped with flowing robes, lost in thought. He gazes out over a chequered floor upon which have stood many of the greatest men and women in the history of the human race.

Several other renowned figures are commemorated in stone around the edge of that ante-chapel, all of whom celebrated alumni of this one place of learning. Among their number stand the intellectual elite of British history: Francis Bacon, a founder of the scientific method; Isaac Barrow, who was fundamental to the development of modern mathematics; Thomas, Baron Macaulay, a parliamentary reformer responsible for the legal system of much of the British empire; William Whewell, a highly accomplished scientist and philosopher; and Alfred, Lord Tennyson who is reputedly the second most quoted writer in the English language, surpassed only by William Shakespeare.

Yet even among these extraordinary superlatives in the field of human genius, only one titanic figure is granted a central place of honour, gazing pensively eastwards, past his contemporaries, towards the high altar.

Our understanding of the Universe around us perhaps owes more to Sir Isaac Newton than to any other human being before or since. He ranks among the greatest geniuses ever to set foot on this Earth, and his legacy has dominated scientific thought of all nations for three centuries. Newton’s most profound discoveries, though they have since been embellished and extended, still lie at the very core of our understanding of the Cosmos.
Inscribed along the base of the statue commemorating this one man are the Latin words, ‘qui genus humanum ingenio superavit’. Loosely translated, “he surpassed the race of men in understanding.” The deeper we look into the achievements that inspired those hyperbolic words, the harder it becomes to deny the accuracy of such an extraordinary, almost worshipful epitaph.

Newton possessed an unparalleled intellect and he understood the natural world with an extraordinary clarity. He was a fierce and prodigious polymath who tirelessly focussed his energy towards a wide range of diverse and distinct challenges, and excelled at them all. He was arguably the most influential founder of the entire global scientific endeavour and his works rank amongst the greatest ever achievements of the human mind.

However…

Despite this extravagant eulogy, it would not be overstepping to mark to say that Isaac Newton knew so little of the physical Universe by the standards that we might set today, that he would fail even the most basic of high-school science examinations. Our world would seem as alien to him as his seventeenth century life would have appeared to a stone-age hunter-gatherer. Every aspect of human civilisation has evolved beyond recognition from that medieval world Newton knew, sometimes in giant and profound leaps, though usually through the slow but steady march of progress which, year after year, has built so extensively on the foundation that he himself provided.

In this book, I aim to show how our society has been shaped by the progress of science, not just through the gadgets and devices upon which it depends, but also by our understanding of the Universe in which we live. Each year we collectively advance one step further away from the word with which Newton would have been familiar, and we uncover yet more vital pieces of the puzzle of the natural world; a conundrum that Newton spent so long struggling to understand.
It is tempting in this age of high technology to fall for the strangely seductive tendency to look back at previous generations with a degree of arrogance, laughing at the mistakes they made, ridiculing the beliefs they held dear and highlighting the extraordinary poverty of their knowledge of the Universe. I think we all, albeit with some understandable guilt, enjoy the feeling of superiority we get when learning of times gone by, when people were primitive enough to believe in such fantasies as witchcraft and bloodletting. It is tempting to think of our distant ancestors as our intellectual inferiors because they were unaware of so many things that we now consider second nature. Tempting, but false, because this picture doesn’t even remotely hold up to a more thorough examination in the light of science or history. Although there are a great many things that were not known in the seventeenth century, the world into which Isaac Newton was born was hardly ignorant.

For example, I challenge any reader of this book to duplicate the feats that the great pioneers had already achieved by the year of Newton’s birth. Medieval explorers knew much about the geography of the Earth and had mapped most of its surface by hand; astronomers knew that our planet was not, as was previously believed, the centre of the Universe, but that it orbits around the Sun, together with the five other planets known at that time, the orbits for which were also accurately studied; engineers had developed the technology to manufacture enormous sailing vessels and to chart their progress accurately across the vast expanse of the open oceans; pioneers had circumnavigated the globe and built trade links spanning the continents, bridging all the distinct societies of the world in the age before multinational corporations and cheap international travel brought the world to our doorstep; architects designed and built towering cathedrals that still dominate the skylines of twenty-first century cities; and last, but not least, creative minds had crafted fine works of art, literature and music which, in many cases, remain unparalleled to this day.
Newton knew and understood all of this; he had studied in great detail the achievements of generations before him right the way back to the great thinkers of antiquity, which dominated most learned thought at the time. He was an accomplished theoretician but was also a talented and thorough experimenter. He was not content merely to build mathematical models of the physical world, but also insisted on testing their accuracy with equal zeal and vigour. In his time, and purely by virtue of his great mind, extraordinary dedication and stubborn perseverance, he became one of the most important men in England, amassed a considerable personal wealth and earned the humble admiration of many otherwise excellent, well-regarded scholars.

I often find myself day-dreaming, imagining how it would feel to meet the greatest minds of human civilisation, long since departed. What would happen if I were to bring them into the modern world – a world which they helped to create but which has now far surpassed anything that they could ever have imagined? Our way of life is certainly profoundly different to theirs, but that’s not purely because of smartphones and high-definition televisions. There’s much more to the picture that we inevitably miss if we focus only on the technological marvels of the information age.

Our world differs from that of Sir Isaac Newton, and all those scientific pioneers before him, by far more than just the physical manifestations of three hundred years of scientific progress. An increased scientific understanding in society has delivered numerous fundamental shifts in the way we think. We no longer suffer the same fears, foster the same beliefs, or nourish the same hopes as did our medieval ancestors. We see things in a different way to the greatest minds of distant generations, and we’re able to do that because of the insights that we, as a society, have gathered for ourselves; Insights that have radically reinvented our relationship with the natural world, with technology, and with each other. The accumulated knowledge of mankind has surged
relentlessly forwards, and that same learning has stealthily filtered into the consciousness of every individual human mind.

When we look out at the sky, we see the same Sun whose light has warmed our ancestors since our species first arose on the African savannah. Yet we no longer marvel at an anthropomorphic god driving celestial horses from a blazing chariot of fire, but rather a giant ball of gas a million times the size of our Earth, four hundred times further away than the moon, burning at unimaginable temperatures through the power of nuclear fusion. When we watch a chimpanzee gazing towards us with its wistful eyes, we marvel at the extraordinary physiological similarities that we now know to be far more than just mere coincidence. When we feel unwell, we talk about germs, viruses and white blood cells, not about witches’ curses, divine wrath and unbalanced humours. The difference between our world and that of ages past is not just one of technology, it is one of perception. We, as a species, have embraced countless shifts in the frame of reference from which we see and interpret the world around us, radically reshaping our everyday experience to such a degree that we are unaware that it would even be possible to understand it differently.

Perception doesn’t just cover our direct physical encounters with the external world. After all, nobody alive has ever seen the structure of an atom with the naked eye, and our understanding of the stars and planets in the Milky Way is based on observations taken with sophisticated telescopes and not merely the wide-eyed night time stargazing that inspired our ancestors to weave an intricate pantheon of fictional beasts in the heavens above. Our understanding of mankind’s place in the cosmos is not based on our own senses, nor on our own direct experiences, but rather on the knowledge that we have gained together as a species, searching for the hidden secrets of the Universe with sophisticated apparatus and theoretical techniques.

The birth and development of science, largely ignited by the work of Sir Isaac Newton, have heralded an entirely new era in human experience.
Our interaction with the world is no longer based on what we, as individuals, experience during our lifetimes, but we now understand together as one single organism. Our individual experience of life is inescapably moulded and amplified by the discoveries made by those thousands of intellectual pioneers who went before us to prepare the way.

The greatest gift that humanity possesses is the ability to benefit and to learn collectively from the work of others. Our inquisitive, highly adaptive minds coupled with our unique innate ability to express ourselves through language, have served to elevate us high above all other animals. This remarkable division of labour, not purely through space but also through time, is what has taken us from the Stone Age to the Information Age. Moreover, it is what has allowed us to develop the whole spectrum of human technological achievements, from flint axes and spears to vaccines, digital computers and nuclear-powered robots on Mars.

This is a book about science, but it is not a science book; nor is it even about Sir Isaac Newton – at least not at its heart. I apologise if you are expecting a detailed and scholarly historical tome. There are plenty of good biographies out there that give you the facts about every intricate detail of Newton’s life – I have consulted many of them to enhance my storytelling, but it was never my plan to write another. There are also vastly many science texts that could tell you all you could ever realistically want to know about the law of gravitation and the mathematical laws that come with it, but I kept this book deliberately free of complicated terminology for a very good reason: My aim for this modest work is something very different. I hope to show how the human race owes a debt to science that stretches far deeper than you may ever have suspected, and I hope to teach you what Science really is - not a list of facts and theories, but a powerful set of techniques that enable us to probe the natural world with unprecedented clarity.
This is a book about human wonder and perception, and how we see the world through the lens of knowledge and understanding. My overriding aim was to show how our interaction with our environment has been crucially shaped by several monumental shifts in understanding that have taken place during the last three centuries. And I will take you through those discoveries in order, introducing you to them as we might introduce them to Isaac Newton in his imaginary journey through time to the present day.

Our journey begins by examining the world as Newton left it. I start this tale by investigating a set of discoveries that remain, even today, as Newton’s best known achievements. I will describe how they provided a shift in perception so enormous that it is a testament to the human mind that it goes unnoticed by almost all of us almost all of the time.

I find that this is the case with many of the most important discoveries ever made. The most influential theories in all science have permeated so deep into our subconscious minds that we don’t even realise that there was once a time before they were known. The greatest compliment anyone could ever pay to any scientific theory is not just to refuse to doubt it, but to refuse to accept that doubt were even possible. To ask, with incredulous surprise, how things could ever be otherwise.

I have chosen to spend just the first chapter of this book introducing the world of science as it was when Isaac Newton departed this world in the early eighteenth century. To dedicate merely one chapter on arguably the greatest scientist who ever lived (and after whom the book is named) might seem a debatable use of resources, I freely admit. However, the pioneering achievement of Isaac Newton’s life was not in creating a great many advancements in a wide diversity of fields - for one thing, there really were no individual scientific disciplines to speak of at the time. On the contrary, Newton’s great contribution was that he brought together all the disparate threads of learning that had recently been crafted by such great figures as Galileo, Kepler and Copernicus (whom we will meet later). He built a theoretical foundation with which
to express them, and then he wove those threads together into a simple, coherent and powerful whole.

Newton was not the only one to realise that the few tentative forays that humankind had made into a new, undiscovered world of knowledge were the first shoots of a scientific renaissance. Even so, he was arguably the only man of the time capable of envisioning the apparatus by which that renaissance could proceed. He spent his life building the foundations on which scientific theory would be constructed for centuries after his death. His most celebrated works brought together the sciences of astronomy, mechanics and optics empowered by new mathematical tools developed by the greatest minds across Europe.

What Newton did, in essence, was to bridge the gap between folk science - that is, the science that human beings had so far managed to invent purely through intuition and anecdote - and a rigorous system of learning that would facilitate all the discoveries that followed.

Until the late seventeenth century, humanity had mainly been wandering around in the darkness, grasping at truths and falsehoods with equal enthusiasm and without any means by which to distinguish between the two. The Newtonian revolution provided a light of reason which gave us the opportunity to discard nonsense and superstition, to identify essential laws of nature, and to begin a steady and unfaltering progress away from our humble origins.

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Newton was hardly a modest man, though in a letter to a fellow scientist he once remarked, “If I have seen further, it is by standing on the shoulders of giants.” I don’t subscribe to the media-friendly cliché that isolated geniuses are responsible for all scientific progress. Not only is that viewpoint patently untrue, but it’s also an insult to the millions of men and women who have worked tirelessly over the history of civilisation to build up this great edifice of human knowledge.
However, it is often those few great minds who give us that first flash of inspiration, the courageous declaration, or the painstaking and obsessive investigation that brings about the birth of a new and exciting insight into the world around us.

This book, I have said, is not about science – it is about the human experience of knowledge. It is, as Newton himself might perhaps have put it, the view from the giants’ shoulders.

Dr Colin Frayn,
London,
May 2014
Fig. 1: Statue of Isaac Newton in the Chapel of Trinity College Cambridge.
Image: Cambridge2000.com
Heaven and Earth

“Whence is it that Nature doth nothing in vain?”

Newton

Isaac Newton very nearly never made it into the world. He was a sickly, pallid baby, born prematurely to a nineteen year-old single mother who had been cruelly widowed towards the end of her pregnancy. Three months after suffering the agonising heartbreak of her husband’s early death, and in the dark and bitter cold of winter, Hannah Newton gave birth to a baby boy - her firstborn child.

It was the middle of the night, in the early hours of Christmas day\(^1\) 1642, in the small Lincolnshire village of Woolsthorpe. For a man who was to spend so much of his life on an incessant quest to seek a common ground between science and religion, this date was a curiously auspicious beginning. Snow lay thick on the ground and the servants sent to bring supplies for the young infant decided not to hurry as they expected, in all likelihood, that young Isaac would be dead by the time they returned.

But against the odds, he survived.

These early health problems were only the beginning of the trials that this new and fragile family would suffer. Hannah Newton was bright and well-educated, and she owned a significant estate, but she clearly

\(^1\) It was Christmas Day, 25\(^{th}\) December, in the Julian Calendar that was in use at the time. Britain did not swap to the modern Gregorian calendar until 1752. By the Gregorian calendar, Newton was born on 4\(^{th}\) January, 1643.
had no desire to bring up a son and manage a large farm on her own. Consequently, young Isaac went from having no father at all for the first three years of his life, to inheriting one he despised as his mother decided to marry a man three times her age. Reverend Barnabas Smith was the rector of a neighbouring parish, and hardly a philanthropist. At 63 he was of a completely different generation from his new wife and, most importantly, wanted nothing to do with the young stepson he had so irritatingly acquired. It seems unlikely, at least to our modern perception, that it could have been a particularly fond marriage.

Many people have argued that Isaac’s famously abrasive personality as an adult may have found a firm footing in these formative years. He spent the first three years of his life in a recently bereaved family, without a father, in times when women were very much second class citizens. And then, when his mother abandoned him to move off down the road with her new husband, Isaac was left with his maternal Grandmother. He was an only, and a lonely, child in a world that didn’t seem to offer him many of the joys of childhood.

This was Isaac’s first experience of the world he was to spend the rest of his life trying to understand through rational means. It can’t have made much sense to this young boy, blessed with a sharp mind but equally cursed with an uncanny skill of alienating himself from all those around him – a skill which he no doubt honed on his new stepfather as he grew older. Isaac managed to retain his childlike inquisitiveness throughout his life, though he also developed a notoriously foul temper and abrasive personality, with predictable results. In almost every story of Isaac Newton’s childhood, and his entire adult life, there is a recurring theme of him abusing his intellect to bully those over whom he had attained any degree of power or influence, and resenting those whom he could not control. This probably began in the playground, but he never seemed to grow out of it, despite a deep insecurity at his heart which robbed him of the emotional strength needed to deal with the predictable repercussions.
Still, Newton made it through his childhood years relatively unscathed and secured a place at Cambridge. As he entered the world of academia, it soon became clear that he could get his own way in practically any academic argument, simply by virtue of his forceful intellect and the formidable advantage he gained by being nearly always right. He made great use of that advantage in the years to come, refusing to bow down intellectually to the acclaimed experts of the time, as would no doubt have been expected. In that sense Newton was at least meritocratic – potential colleagues had to earn his respect first, though almost nobody ever did.

The world in which Newton lived and worked was one without any of those noble principles that we would today regard as the fundamental tenets of scientific research. Science, philosophy and theology all merged into one diffuse and nebulous whole. There was only one degree course in Cambridge at the time, and it had compulsory examinations in ancient Greek, Latin and Hebrew, together with Old- and New Testament theology and studies based around the classical Philosophy of Plato and Aristotle. The aim of the Cambridge degree was primarily to churn out intelligent and well-read clergy for the Church of England. Mathematics and Physics were side-subjects, included to round-off the students’ understanding of the natural world, but hardly to offer them a solid grounding for a career in research. But then again, the cutting edge of science at this time was really rather blunt.

The sharp contrast with modern day Universities could hardly be clearer. Today students are encouraged to specialise over the course of their degree into an increasingly narrow area of study, and it is held as self-evident that all levels of education should be open to students from any background, male or female, rich or poor, dependent only on their desire and ability to learn. It would be intriguing to see what Newton would think of our modern education system in which the acquisition of knowledge is considered to be a right of the masses, not just of a privileged few. It would perhaps be even more interesting to see what
his opinion might be of the way in which universities have abandoned the single, theologically-inspired courses that they previously taught to all their students, and now offer specialist degrees in mathematics, physics, chemistry and biology, in the humanities, languages and arts, in economics, law, medicine and countless other subjects in between. If Newton had been given the choice of a first degree in a specialist science, instead of one which was essentially theology, would he have taken it? At this early stage, it was not at all clear whether he considered himself a theologian who dabbled in natural philosophy, or a philosopher with a fascination for religion. The line was considerably less marked than it would be today.

However, even given the distinctly theological emphasis within 17th Century academia, the most conspicuous difference as far as we are concerned was the total absence of anything remotely approximating a rigorous process of investigation into the natural world. Debate had continued for two thousand years according to the Greek school of thought which resembled folk philosophy and rhetoric more than science. Obvious though it may seem to our modern ears, Newton was one of the few people in almost two millennia who actually suggested that scientific propositions should be rigorously defined and then tested through controlled experimentation in order to determine whether or not they actually held true. Thought alone was not always enough.

Yet that was not an uncontroversial opinion. The man perhaps most closely linked with the birth of modern scientific thinking, besides Newton, was Galileo Galilei (1564 – 1642), who had died almost exactly one year before Newton’s birth. Galileo spent the final eight years of his life under house arrest for daring to suggest, in oppressively Catholic 17th century Italy, that the Earth might not be the fixed centre of the Universe and instead, as the Polish astronomer Nicolaus Copernicus (1473 - 1543) had declared a century earlier, that the Sun might lie at the centre of the solar system with the Earth and the planets simply orbiting around it. This bold assertion almost cost Galileo his life, and only by recanting under extreme duress, and relying on his
former friendship with Pope Urban VIII, was he able to reduce his sentence to house arrest.

Galileo was the right person to be making such assertions, which fitted beautifully with the observations that he had been making with his new invention – the telescope. But apparently the heliocentric (sun-centred) model was never going to be deemed acceptable with the authorities. This wasn’t because Galileo provided insufficient evidence for his claims – his observations were incontrovertible. Nor was it because the theory was implausible for some deep mathematical reason – in fact, it greatly simplified the mathematics of celestial dynamics. No, the theory was opposed merely because it wasn’t what people at the time wanted to believe.

I could quite easily have dedicated several chapters of this book to the life and works of Galileo, who not only popularised the heliocentric revolution, forcing the religious establishment to abandon beliefs held since the birth of civilisation, but who also invented the telescope and encouraged the incorporation of mathematics into the understanding of physical laws. Galileo was the first person ever in the entire history of the human species to peer with trepidation through the lens of an astronomical telescope. He was the first to observe the four most prominent moons of Jupiter that now collectively bear his name; he was the first to discover the majestic rings of Saturn; he was the first to examine the mysterious nebulae and the first to witness globular clusters where hundreds of thousands of stars jostle together in a seething mass of nuclear fire.

The invention of the telescope, and indeed the microscope, which came along at roughly the same time, were extraordinary landmarks in the history of human knowledge. For Galileo, resting his eye nervously on the glass for the first time and gazing heavenward, it must have been a staggering, life-changing experience. He had opened a door to an extraordinary but dangerous new world; a wealth of new experiences that were as incomprehensible and revolutionary for him as it must be
for modern day explorers diving to the depths of the ocean’s deepest and darkest trenches and discovering creatures so spectacularly alien that they exceed even our most fantastic imaginations. The telescope opened up a world that no human had ever seen.

Despite continued religious opposition, the scientific community had accepted the heliocentric theory by the end of the 17th century, though Copernicus’s extraordinary book in which he first suggested the idea, *De revolutionibus orbium coelestium* (“On the Revolutions of the Celestial Spheres”) remained on the Catholic Church’s list of banned publications until 1835. Then, better late than never, in 1992, Pope John Paul II finally pardoned Galileo for his ‘heresy’ and offered an apology, a mere three-and-a-half centuries after the great scientist’s death.

Progress, in the time of Newton as much as today, was often held back by those who did not want new discoveries displacing their established beliefs. The celebrated 20th century physicist Max Planck once remarked that “a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die and a new generation grows up that is familiar with it.”² There are few humans with enough courage to admit that they have spent a lifetime pursuing a falsehood. Newton himself was not one of them, as we shall see in a later chapter. Though perhaps it took a man of Newton’s temperament, who certainly didn’t seem to mind causing offence to anyone he met, to put forward a new way of thinking that would overturn almost two millennia of deeply entrenched beliefs.

So which of Newton’s discoveries would we today find familiar? When most people are asked to name the one theory for which Newton was most well-known, they usually mention the story of the apple which dropped to the ground, or perhaps fell on Newton’s head, and caused him to invent the Theory of Gravity. The story is probably a fiction, but it at least serves as a fine example of the way Newton’s mind was

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working, and how his analytical powers began to piece together a rational picture of physics.

As the story goes, Newton was back at his mother’s house in Lincolnshire in 1665 and 1666, avoiding the bubonic plague which was busy slaying its way through a substantial proportion of the population of London and surrounding regions. He was allegedly sitting in a field pondering the mysteries of the Universe, when he witnessed an apple drop from the bough of a tree, and he was struck by a curious line of thought that had never occurred to him before. In order for the apple to fall - to leave its state of rest - it must have been pulled (or pushed) by some kind of force. And hence, the theory of gravity was born.

Whether or not this event happened as Newton recalled we shall never know, but the story has stuck because it’s such a wonderful example of the way in which physics has completely reframed the way we interpret the world. The insight seems to us today to be embarrassingly obvious and one wonders not only why it took the greatest mind of his time to think of it, but more to the point, why he bothered boasting about the discovery, and even wrote a book about it. In Latin.

To understand why this took such a great genius to suggest, we must put ourselves back in the frame of mind of the average seventeenth century scholar. The prevailing opinion, still held even amongst the professors at Cambridge in Newton’s time as an undergraduate, was the belief inherited from the Greek philosopher Aristotle (384 – 322 BC), which stated that objects had their natural states, which they endeavoured to obtain whenever possible. The natural state for an apple was to lie on the ground (an apple being composed of earth and water, whose natural place is therefore slightly above that of earth), and so as soon as it broke free from the clutches of its parent tree, that was exactly what it attempted to do, as rapidly as possible.

But Newton had been working on something very different; a fundamental unification of two ideas that revolutionised the way the
world understood rest and motion. It was a set of laws so vital to the understanding of the physical Universe that they still bear the name of their discoverer. Newton’s insight was based on the proposition by his predecessor, Galileo, that \textit{rest} and \textit{motion} are the same kind of thing. For all of time, human beings had watched moving objects and stationary objects, and placed them in two distinct categories, but Galileo had seen a fundamental similarity.

You have, no doubt, had the experience of gazing out of a train window at another nearby train which appeared absolutely stationary despite the fact that both trains were moving at high speed in exactly the same direction. What Galileo noticed was that the concept of \textit{motion} was relative. Two moving objects, like those two trains, appear at rest relative to each other, and the only way you can say that they are moving is with reference to another object, such as the trees alongside the track. Without any other objects to measure against, it means nothing to say that the trains are moving at all.

You are probably thinking now that you could, of course, say that trains can be said to be in motion if they are moving along the track, and that we can use the Earth as a frame of rest. But then what would an observer sitting on the moon or, if it were possible, on the Sun, think? They would imagine themselves to be stationary, and the Earth, track, trains and all to be whistling by at an enormous speed as the entire planet flew past. So even the Earth isn’t a universal frame of rest against which any speed must be measured. In fact, there is no such thing as a fundamental location and speed against which all others should be measured. So when we think of a ball rolling along the floor, and another one apparently stationary next to it, we must realise that the state of motion and the state of rest are merely illusions caused by our own particular perception. Who is to say that one ball is moving and the other stationary? And once we’ve realised that, we’re already ahead of the greatest minds in the world at the beginning of the seventeenth century.
Working from Galileo’s theory, Newton realised that an object at rest is therefore exactly the same as an object travelling in a uniform motion with a constant speed – ‘rest’ was just a special case where the speed was zero relative to whatever we considered to be our reference. And he showed that objects will continue moving at exactly the same speed and in the same direction unless some external force diverts them. Then, when a force does act upon the object, it causes acceleration – that is to say, the object changes speed, and the amount its speed changes increases with the strength of the force and is resisted by the object’s mass.

These were Newton’s first two laws of motion. In everyday terminology, they reduce to the following two observations:

1. Objects tend to continue at rest, or move at a constant speed, unless some external force acts on them.
2. When an external force does act, the object changes speed. The stronger the force, the greater the change in speed. More massive objects require a stronger push to achieve the same change in speed.

These seem rather unremarkable, but it’s easy to overlook the fact that they were utterly revolutionary in Newton’s day. He also added a third law, which was perhaps even more perceptive. Newton realised that, in the case of the apple on the tree, it was being pulled downwards by gravity all the time, and the only reason why it didn’t fall down beforehand was because the tree was pulling it up with an exactly equal force in the opposite direction, and these two forces precisely cancelled out. So the third law, perhaps the most famous of the three, states:

3. Every action has an equal and opposite reaction.

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3 Strictly speaking, the velocity changes. Speed is a measure of how fast an object is moving, and velocity measures the speed and direction. So a force can push an object and cause it to move in a different direction, but at the same speed. In fact, this is what happens with circular orbits.
The simplest example is seen when you sit in a boat and push hard on the river bank. The river bank also pushes back on the boat with an equal force, causing the boat to move away from it. The astute reader might also notice that, if you think about it, this means that you are also pushing the Earth away from you. Of course, your push isn’t going to move the Earth very much because the Earth has a huge mass with which to resist your push. Similarly, every time you jump upwards, you’re pushing the Earth downwards, though gravity pulls you back together soon afterwards.

Newton’s laws seem self-evident to us today. What could possibly be so controversial about such a simple set of statements concerning the mechanisms underlying nature? Well, recall the view of the ancient Greeks, whose model of physics had filtered through the ages, barely unchanged since Aristotle nearly two millennia earlier. The Greeks believed that every object had its own set of behaviours based on its essential properties and potential. Thus, a stone was destined to sit around doing nothing, and not to fly through the air unless picked up and flung. Why? Because it was composed primarily of the element of Earth. As Earth was the centre-most, and hence the lowest, of all the elements, objects composed of Earth would always tend to move downwards whenever placed in an environment composed of any of the other elements - air, water or fire. Water falls through fire and air, but does not fall through Earth because it is superior to Earth. Air floats on water and earth, but falls through fire, and fire, the highest of the four main elements, grasps ever heavenward, searching for its true position above the other three.

The Greek theory was elegant and, with a little shoehorning, could be made to fit most observations that people tended to make, most of the time. Moreover, it was simple enough that everyone could understand it – and that was its great strength, and the reason why it had prevailed for so long. It was intuitively obvious, and provided an explanation of
nature that fitted well with the human tendency to ascribe human-like traits and hierarchies to all things.

But it wasn’t intuitively obvious to Newton – it just didn’t sit right with him at all. In fact, it all seemed rather *ad hoc* to assign such arbitrary, almost *sentient*, properties to inanimate objects. And once Newton got an idea he very rarely let go. Struggling with the weakness of the existing theory, Newton spent much of his early Cambridge years building up his own theory of motion, consisting of the three laws we’ve already seen, plus a number of other astute and revolutionary observations.

Aristotelian physics wasn’t the only ‘intuitively obvious’ theory that Newton intellectually dismantled. Much of his other most important original work was in the field of optics, dealing with the properties of light. He was the first to realise that light was composed of many different colours all at once, and that objects appear to us as a certain colour because they reflect only certain components of the light back to our eyes. He based this theory on a series of painstakingly accurate experiments that he conducted in his rooms in Cambridge, with finely positioned prisms projecting a wide spectrum of light in all its colours across his study wall. Newton’s great theory was incomplete, of course, as he didn’t know how light was actually transmitted. He couldn’t really have been expected to know - it wasn’t until the nineteenth century that these secrets were eventually unravelled. Though that didn’t stop him making a few guesses, and he wasn’t far off.

Newton’s theory on optics was initially greeted with a mixture of intrigue and doubt. Many rivals, who naturally had their own theories to promote, thought that Newton’s conclusions were altogether unjustified. Consequently many tried and failed to replicate Newton’s original experimental results, usually because their methods were a great deal less precise and often because they simply didn’t understand what it was that Newton had actually done. Several, it has to be said, probably also lied. Newton grew exceedingly frustrated with the
intrusions into his life caused by dissenting scientists demanding that he address their complaints. To him, the theory was decided beyond any doubt and he resented the implication from lesser minds that he might have been mistaken on the subject. He was right, of course, though that didn’t stop the dissenters from forcefully protecting their own pride.

Newton’s theory of optics was a fine example of why he is so justly revered. His experimental accuracy was unparalleled, and his measurements were extraordinarily precise given the lack of modern instruments. His techniques were often ingenious, demonstrating a combination of thorough theoretical understanding of the physics involved, and a masterful grasp of practical skills such as lens grinding and carpentry. The theory of optics was a particularly good example of Newton’s legacy because it marked the advent of rigorous, methodical experimentation as a departure from ‘folk science’.

Folk science, like that of Aristotle⁴, is that way of understanding the Universe which is most natural to us as human beings – the form of investigation based merely on intuition and not on experiment or theoretical analysis. Our sense of intuition is actually rather good for many everyday tasks, which is precisely why it evolved. But when it comes to understanding the physical world on a precise, scientific level, our intuition begins to break down. In fact, in many cases it’s actually a hindrance rather than a help. In a very important sense, science is the process that humanity has come up with to remove our own fallible cognition as much as possible from the process of learning.

We will see in later chapters how our remarkable brains evolved primarily to cope with the demands of a hunter-gatherer lifestyle on the African plains. We will learn how our instincts are often able to perceive things that even the most sensitive of modern technology struggles to detect. To the Greek Natural Philosophers, though they would probably have denied it, instinct was everything. It was obvious

⁴ No doubt I’m being hugely rude to one of the greatest minds who ever lived, but he can’t sue me anymore.
that everything was composed of four elements, because objects behaved exactly in that way. The picture was always self-consistent because it was so fundamentally tuneable. Theory could modify itself so that it was always guaranteed to match the results.\(^5\)

To the ancient Greeks it was obvious, for example, that objects at motion must be pushed by a force to keep them moving because that was what happened when a cart was pushed through the streets of Athens. After all, if one stopped pushing the cart, it returned to its natural state of rest rather quickly. So, if a stone arches through the air, it must itself be exerting a force on its surroundings, in much the same way as a bird does when following the same trajectory. Newton’s claim went against folk physics, because he was able to imagine a simple world, stripped of the complications of intuition and ‘common sense’. Intuition works rather well in everyday survival situations, but rather poorly when attempting to build the foundations for a rigorous theory of universal motion.

What Newton achieved with his laws of motion was not only the realisation that rest and uniform motion were the same, but also that there was really only one property of any object that was of any relevance whatsoever to its dynamics, and that is its mass. Strictly speaking, its *inertial mass* – its ability to resist the action of any force. When you apply a force to any object, its acceleration varies inversely with the mass of that object. That is to say, if the mass of an object is doubled, an equal force applied to it only causes half as much acceleration. No earth, no water, no air and no fire; no ‘innate potential’ concealing a mysterious goal-directed purpose in nature, no natural state of being. Just mass. And *everything* has mass\(^6\). Newton’s physics worked just as well on an apple as it worked on a stone, or a herring, or the Pope, or the planet Jupiter, or an entire galaxy. All things

\(^5\) Indeed, there are some who make the same complaint about certain particularly theoretical and speculative branches of modern physics, but that is a story for another day.

\(^6\) Well… *nearly* everything. Don’t get ahead of yourself.
were equal under the unifying power of Newton’s physics. Man was no more than a grain of sand or a speck of dust; and no less than the highest mountains or the great expanse of the oceans. It was a revolution.

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There is a great debate in scientific circles about the balance between wonder and understanding. Is it possible to study something to such a degree that we understand it with perfect clarity, and yet still retain some of that same wonder that first drove us to learn? The life of Isaac Newton answers that question affirmatively and undeniably. It is a theme to which I will return many times before the end of this book.

The history of science is one of demolishing superstition, and shining light in dark places where once dwelt our fears and our naïve wonder. Science is not, nor has ever been, first and foremost about obtaining the greatest happiness or pleasure – it is a quest for understanding. Transforming the truths that science obtains into constructive and beneficial institutions is the job of politics and economics. The fiercest debate of the 21st Century will not be about war, famine or disease – it will be about knowledge. How far can we go? How far should we go? How is our pursuit for omniscience affecting our society, and how should we answer those difficult questions that are impinging on our collective morality at an alarmingly accelerated rate?

I would humbly suggest that the success of our species is in no way increased through ignorance. Quite the opposite – it is a lack of learning, coupled with the stifling of intellectual freedom and the imposition of unquestionable dogma that have lurked behind all of humanity’s darkest moments.

For Isaac Newton, science meant something extremely personal. Though he was a deeply religious man, Newton firmly believed that the pursuit of science was the best way to explore and experience what he saw as the hand and mind of God in creation. His faith stemmed from
his early childhood, no doubt inherited verbally from his mother and stepfather. The Rev. Smith had a substantial selection of books on theology which the young and eager Newton would have devoured with his characteristic single-minded dedication. Indeed, young Isaac inherited this extensive library when, as an 11 year old boy, he found himself fatherless for a second time on the death of his stepfather.

Newton’s religious views were far from orthodox. The greatest irony being that, despite his position as a Fellow at Trinity College, he was firmly opposed to the doctrine of the Holy Trinity – the Christian idea that God is somehow one being in three components. This idea had formed a bedrock of Christian doctrine since the year 325CE, when the early church leaders had met to thrash out the fine details of their belief system. Newton kept his heretical ideas closely to himself, knowing that the punishment for such damnable views would certainly include a removal of his fellowship and the effective end to any hope of a career in academia, or elsewhere – but he remained passionately opposed to many of the central tenets of Christian teaching throughout his life, despite retaining a deep faith in God as he perceived him.

To Newton, no mystery – especially the divine – was beyond the realm of his inquisitive mind. It seems surprising that so many people at the time accepted the Aristotelian beliefs that divided up all objects between the elements, and assigned each object its potential, but so few people actually ever took the time to question whether or not it was actually true in any dependable sense. It would be wrong to claim that Newton invented the scientific theory, but it would certainly not be overstepping the mark to say that he was the first to demonstrate how it could and should be applied universally, without exception and without prejudice, to the study of any subject of importance. To Newton, God gave us brains, the gift of curiosity and the intelligence to back it up, and to squander those gifts was an unforgiveable sin.

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So what is this whole “science” thing that Newton helped to begin? Well science, as a process, exists to solve one simple, two-part conundrum: How does the Universe work, and how do we know that we are not mistaken? Scientists are often accused of arrogance because of their regularly undiplomatic claims to absolute knowledge – they often appear strikingly confident in their views. Fundamentally, however, science was formed with the emphatic purpose of erasing arrogance from our model of the Universe. That is not to say that there are no arrogant scientists – one need not work in academia for very long to discover otherwise – but the scientific process is exactly the opposite. Scientific method realises that humans are fallible, and hence that evidence taken from hearsay, intuition, fiat, dogma, wishes, emotions, desires, or anecdote – no matter how convincingly and heartfelt these often may be, and regardless of the stature of the human being claiming them – is essentially worthless as a basis for building a solid foundational model of the Universe. We need something more. Something better.

So, to reiterate, science determines to ask not just the question “How does the Universe work?” but also the rather more important corollary: “How do we know that we are not mistaken?” And this second question is the one that ignited a transformation that began with Isaac Newton and blazes unabated to this day. Science is not happy merely with a hypothesis – a ‘guess’ at the way the Universe may work – no matter how well thought-out it may be, nor how many intelligent people already believe it. Science demands more than this – it asks for proof. And science demands a very special standard of proof that is above what we, as normal human beings, often regard as sufficient in our daily lives. When you are attempting to build an enduring legacy of knowledge, you need to be certain that your conclusions are correct, and you need to know exactly what kind of evidence could persuade you to change your mind. And, most importantly, if that evidence does arrive, you need to accept that the former picture was probably wrong, and move on.
This was especially important with the theories that Newton was proposing which must have seemed mystical, even magical to many of his contemporaries. How could a hitherto unknown force be acting on an apple to pull it down to the ground? How could any one body exert an influence on another at a distance without any visible tether? These were sensible questions, and there was no doubt that Newton’s theory, though simpler in many ways, opened the doors to some vastly more complex questions further down the line. The concept of “action at a distance”, as Newton was suggesting, seemed more magical and less scientific than the theory he was attempting to replace. If Newton was going to make such extravagant claims, he knew that he was going to have to back them up with huge amounts of evidence and rigorous argumentation.

When faced with several competing theories, which one should we choose? In the next chapter, I will introduce a number of vital developments that took place in the years after Newton’s death which allowed scientists to formalise this process, but even in Newton’s time there were principles that could be used to sift through a mountain of theories and carefully evaluate their respective merits.

One figure whose thinking influenced this debate was William of Occam, a Franciscan Friar who died almost three hundred years before Newton was born, but who is said to have invented the logical device which now bears his name, Occam’s Razor. The concept is simple, probably far too simple for any one scholar to have claimed its unique discovery, but the Latin phrase, entia non sunt multiplicanda praeter necessitatem (very loosely translated, “theories should never be made more complicated than necessary”), dubiously attributed to Occam, seems to have stuck. Occam probably became most closely associated with the idea because it seems to have been a core theme throughout his writings, though the actual phrase as given above does not actually arise anywhere in his work.
Occam’s razor appears, at first glance, to be such a straightforward claim – why make explanations more complicated than is absolutely necessary to explain what you see? But, of course, it has wide ranging implications and, though it forms the very heart of scientific theory, is based more on convenience than any sound logical footing. Yet all forms of learning would be literally impossible without it. After all, Occam’s razor gives us a mechanism by which we can distinguish between the infinity of potential explanations for any observation.

You may be familiar with the ‘next number in a sequence’ questions that often occur on intelligence tests. Problems like this one:

\[\text{Which number is next in the series: } 1, 2, 4, 8, 16, \ldots?\]

Most people will reply ‘32’, because each term in the sequence is twice the one immediately preceding it. But this puzzle is far more mysterious than it seems at first. Although the answer ‘32’ is fully compatible with the sequence and is probably the most sensible deduction, it’s not the only potential solution. For example, what if the series were something like “To get the next term in the series, multiply the current term by twice the number of its digits”? In this case, the next number in the sequence would perfectly logically equal 64. (16 has two digits, twice 2 is 4, and 16 times 4 = 64.) There are, of course an infinite number of potential sequences that would give the first five terms above, but different sixth terms. For example “Start at 1, then each term is double the last, until the sixth term, which is 437”.

As Occam’s razor shows, there is really only one sensible course of action to take in this situation, without which we can never learn anything. We must always take the potential explanation that requires the fewest suppositions, and the smallest number of tuneable parameters. We must prefer simplicity over complexity at every possible junction.
In the twentieth century, this fundamental notion would be incorporated into the newly developing field of *Information Theory*. The Russian mathematician Andrei Kolmogorov (1903 - 1987) showed, in the late 1950s, that the complexity of any information could be considered to relate to the size of the shortest possible set of instructions that would recreate it. In the example above with the doubling series of numbers, it’s easy to see that the first potential answer is far simpler than the subsequent ones:

*Start with 1*

*Double the previous result each term*

Compared with:

*Start with 1*

*Each term is equal to double the previous term times the number of digits in the previous term.*

Or even this more bizarre version:

*Start with 1*

*Double the previous result each term*

*Except for the sixth term, which is 437.*

With a combination of Occam’s razor, and something that looks more-or-less like Kolmogorov complexity, we should therefore prefer the first answer to the question of which number comes next in the series, even though we acknowledge that the evidence is insufficient to prove that this answer is definitely correct, and that there are, indeed, an infinite number of alternatives. A sensible scientist would wait and discover what the next number actually turned out to be. If it were 32 then the scientist could gain more confidence in the “doubling each step” theory. However, if it were actually 64, or 437, or twelve million, then we would have to throw out the doubling theory, and look for something else.
Occam’s razor seems haphazard and unscientific, and I suppose it is. After all, there’s no actual law of the Universe that says that things are always as simple as they could possibly be. In fact, things often don’t work out that way. But science must adhere to a principle of parsimony, where we never add anything to our theories of the Universe that we don’t absolutely require. The reason for this is simple: Although physical laws often do turn out to be more complicated than we at first presumed, we don’t know what the form that this extra complexity might take, so it would be foolish to include an arbitrary guess in our equations.

Newton could easily have added in a term into his law of gravitation that said that “any two objects attract each other with a force proportional to the product of their masses and inversely proportional to the square of their separation except when the two objects are purple giraffes, and they are suspended from the roof of Westminster Abbey in London on a rainy Wednesday in April.” That theory also agrees with all the available evidence, and so in the absence of Occam’s razor, should be considered on equal footing with the original law. But Occam’s razor allows us to discard it. Unless, of course, those extra terms become necessary as a result of some particularly bizarre and unexpected experimental results.

Newton must have applied this thought process when sinking his teeth into the problems of motion and of gravitation. After all, which is the simplest, most parsimonious explanation: that every individual object and creature in existence has its own unique, predestined and immeasurable purpose that must be determined separately; or that every single object behaves identically under a set of laws that are consistent for any situation, and which depend only on one single, easily measurable property? Folk physics may be intuitive, but it does certainly create a hugely complicated model of the Universe when you’re trying to do anything more advanced than counting sheep or throwing spears at wildebeest.
Some philosophers have tried to claim that Newtonian gravity is a highly complex idea because it introduces a force that applies to every single pair of objects in the entire known Universe, and there are exceedingly many such objects, often separated by extraordinarily large distances. But that objection completely misunderstands the idea of complexity that I have just introduced. Complexity is not about how difficult it would be for a human being with a calculator to work out an answer, but rather it’s about how difficult it would be to describe the law itself – because that is all that nature’s laws must do. The simplest law is obviously the one where every single item in the Universe is treated the same way – there are no exceptions, no arbitrary maximum ranges or filters based on size, colour or density. Just one single law, operating on one single property – mass – and nothing else.

Science was, and is, a force for simplicity. Science was able to cut through the accumulated millennia of superstition and folklore that even the most educated of seventeenth century intelligentsia would have accepted without quarrel. What Newton showed in his lifetime was his intense desire to understand the true laws behind the Universe, not merely being satisfied to accept that things were as they were just because that was how he had always been taught. Perhaps his own personal arrogance helped him along that path – Newton was never under the modest illusion that his teachers knew better than he did. To Newton it didn’t matter where his theories came from, they were all to be examined rigorously by his own methods and his own experimentation before he was satisfied.

This filtered through even into his intense religious convictions. Newton was not happy to accept Biblical versions of history without testing and probing them to see if they stood up to the scrutiny of his formidable intellect. He spent much of his life investigating in great depth the scriptures with which he was so familiar, writing theories about the dimensions of Old Testament temples, and analysing biblical passages in an intensely detailed, even frantic manner. Newton was searching not to displace the divine from his models of the Universe,
but rather to explore the intricate details of the cosmos so that he would better know the mind of the being he saw as its creator, and thus come to an appreciation of the natural world in his own terms. A religion based purely on faith, in Newton’s eyes, was worthless – a lazy insult to an ingenious creator God.

One of Newton’s illustrious predecessors, Francis Bacon, whom we met in our earlier tour of Trinity College Chapel, would no doubt have agreed. He wrote in his book *The Advancement of Learning*, that “all knowledge and wonder (which is the seed of knowledge) is an impression of pleasure in itself.”7 Newton, as an intellectual descendant of Bacon, would have been aware of Bacon’s work, and almost certainly shared his opinions in this regard. Bacon himself was one of the men who first attempted to design a reliable scientific method, of the type that so dominated Newton’s way of thinking.

Scientists are often criticised for wishing to explain the mysterious; to shine light on the unknown. The poet John Keats famously complained about Newton’s disregard for the delicacy of artistic fantasy, and how science aimed to

“...clip an Angel's wings,
Conquer all mysteries by rule and line,
Empty the haunted air, and gnomed mine –
Unweave a rainbow.”8

Newton saw it very differently. He had little time for the arts, having attended an opera only once and, if the stories are to be believed, walked out before its conclusion through boredom. For him, the quest for knowledge was the greatest source of wonder and pleasure he could ever imagine. To remain ignorant or deluded was incomprehensible to him, perhaps even immoral. To strive after understanding was, in Newton’s eyes, the ultimate purpose to which any human being could

7 Bacon, *The Advancement of Learning* (1605), Book I, i, 3
8 John Keats, *Lamia*, 1820
ever aspire. In this respect, he mirrored the opinion of the Greek philosophers, though sadly very few of his contemporaries at Cambridge who evidently seemed content to read the classics but never to pay any attention to anything they said.

This debate still continues into the 21st Century, flaring up occasionally when a particularly juicy bastion of humanity falls to the ever encroaching onslaught of science. The influence of scientific discoveries extends in cold indifference across the boundaries of the sanctified and comfortable beliefs around which our ancestors had built their entire lives. Science has no interest in human emotion – the truth is not a matter of opinion, dogma or desire. No human opposition, no matter how loud, rich or powerful they may be, could dictate the truth as they wished to find it, and the seventeenth century was the first time in history that this had ever been the case. Science stood up against the purveyors of inflexible, unquestioning dogma, and countered their volleys of rage and indignation with clarity, force and unflinching conviction.

Francis Bacon was perhaps also more prescient than even Newton would have admitted. Concerning the motivation for the search for knowledge, he wrote that

“...men have entered into a desire of learning and knowledge, sometimes upon a natural curiosity and inquisitive appetite; sometimes to entertain their minds with variety and delight; sometimes for ornament and reputation; and sometimes to enable them to victory of wit and contradiction; and most times for lucre and profession; and seldom sincerely to give a true account of their gift of reason, to the benefit and use of men”

9 Bacon, The advancement of learning (1605), Book I, v, 11
Though Newton was prone to using his intelligence as a weapon with which he frequently battered his foes, he at least had pure motives at heart. For him, the search for true knowledge was the ultimate goal, and one that consumed him for his entire life.

Isaac Newton died in March 1727, at the exceptional age of 84 years. Having been remarkably healthy for his entire life, his final days were spent in intense pain brought about by a kidney stone for which, at the time, there was no effective cure. He had accumulated an enormous sum of money in his long life, yet he left no widow, no children, and very few friends. It had been obvious to him since childhood that his only contribution to humankind would be the abundant fruits of his unsurpassed investigation into the natural world. This was to be his enduring legacy.

It seems odd to end the first chapter of a book with the death of its title character, but that is where our journey through the history of scientific discovery has brought us. This much is all Isaac Newton ever knew in his lifetime, and from here on every subsequent chapter of this book introduces revolutions in scientific thought that propel us, one step at a time, further away from the world Isaac Newton knew, and towards the present day, still in the dim and distant future.

We can never know how Newton would have responded to these new findings. No doubt some would have been welcome and exciting, and others terrifying, tragic or confusing. Some would have inspired rage, some excitement, some moral indignation. Thus far I have introduced the state of scientific knowledge as it stood in 1727, as the great man breathed his last. It is from this point that we pluck Newton from his eternal repose and guide him with trepidation through the discoveries that, in less than three centuries, have transformed his society into ours.
Having spent some time looking at Newton’s life, and the pure intellectual analysis that consumed him, it’s time for a shift in direction. The next transformational era in scientific progress, and indeed in world history, was to come from a completely different sphere of study. And this time, rather than being discussed in the ivory towers of academia by a small group of learned intellectuals, this new revolution would completely change the path of human civilisation and usher in a new era of extraordinary social change and staggering prosperity.

Let Newton’s education begin.
Industry

“If I had stayed for other people to make my tools and things for me, I had never made anything.”

Newton

The achievements of humanity have always been limited by a few inescapable truths. There are only twenty-four hours in each day, only 365 days in a year and, until the last few hundred years at least, only about thirty or forty productive years in a human lifetime. The great civilisations of history had achieved many astounding accomplishments, but only because our species has an extraordinary innate ability to work together to achieve a common goal, voluntarily or otherwise. The Great Pyramids at Giza, so it is estimated, were the work of over thirty thousand men labouring over the course of eighty years, and those magnificent edifices stand to this day.\(^\text{10}\)

Yet in the twenty-first century, as I write this paragraph, the world’s tallest skyscraper is the Burj Khalifa in Dubai. It stands nearly a kilometre in height, was completed in just six years and with only a fraction of the workforce that the Egyptians had. And it has a swimming pool 76 floors up.\(^\text{11}\) What has caused such an extraordinary leap in productivity in such a short period of time compared to the lifetime of our species? In ten thousand years we progressed from mud huts to pyramids, and in another four-and-a-half thousand years we have constructed buildings so tall that, if you dropped a coin from the

\(^{10}\) The Complete Pyramids (Solving the Ancient Mysteries). Lehner, Mark (1997), Thames and Hudson, Ltd.

\(^{11}\) http://www.burjkhalifa.ae/
top, and even in the absence of air resistance, it would still take nearly thirteen seconds before it hit the ground.

We are, of course, biologically identical to the Egyptian pyramid builders and, before them, our Neolithic ancestors. We have a richer diet now, which admittedly allows us to grow taller, and build larger muscles, but we can only explain a small increase in productivity this way – hardly enough to bring the advances that we see towering above us in the major cities of the world.

There are a great number of mechanical inventions which played their part in this extraordinary transformation of our capabilities as a species, such as coal-fired furnaces and cotton spinning machines, each of which had an enormous impact on human civilisation. But the greatest leap forward of all came from a discovery which revolutionised the way we could generate power and harness it to increase our productive output. And its potential was so broad that it ignited the touch paper on the greatest social revolution in human history.

I feel it my duty to warn you at this point that the topic of this chapter is firmly rooted in the one area of science that is quite literally impossible to make interesting. Many have tried, but all have failed, albeit to differing degrees. That topic is thermodynamics – the single most boring topic in all of physics. Some might think that I am somehow shirking my responsibility to ignite a love of science in every single reader. But, then again, if I were attempting to educate a fresh visitor to England of the beauty of my country, I would take him or her to the great cathedrals, castles and palaces – and I would not be offering a guided tour of the industrial estates of Slough.

So I have made a decision which some of you may consider strange. Instead of attempting to explain this most tedious of academic subjects, I will instead explain how a Frenchman with a kettle directly kick-started a chain of events that made Great Britain the most powerful
nation on Earth. And the tale begins, as most good tales do, many thousands of years ago.

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For the vast majority of human history, the only way to get work done was to do it ourselves. Mr Ugg, the stereotypical Neolithic hunter-gatherer, killed creatures for meat, fur and leather, primarily by throwing sharpened rocks at them. Even when combining with a gang of his similarly-armed neighbours, there was a maximum rate at which he could slaughter the local wildlife and, besides, there was only a certain amount of meat he and his family could eat at any one time.

This all changed when long-distance trade entered the picture. Thanks to this wonderful discovery a superfluous stock of meat and hides could be traded with hungry neighbours for other desirable commodities. Those commodities could be material possessions like fine clothes, sharper rocks or jewellery. Or they could be less tangible desirables such as land, military alliances or a potential Mrs Ugg. Having lots of things other people wanted was now even more desirable than before, though of course it also meant that others would start scheming behind your back to take what you had, by force if necessary.

So the invention of trade produced a considerable incentive to maximise productivity, and after the development of agriculture began to spread between the early civilisations, there was now a fine opportunity to be taken. By supplying others with what they wanted you could make friends and develop influence, but you could also swap things that you had plenty of for things you were lacking.

Every human tribe throughout the short history of our remarkable species has always endeavoured to provide for itself as well as circumstances allowed. Up until the last few thousand years, this meant each individual toiling with bare hands to gather or hunt for food in order to survive. The arrival of Civilisation changed that, allowing us to specialise into certain specific roles, confident that the needs that we
could not satisfy by ourselves would be adequately fulfilled by someone else. Thus the ‘day job’ was born. The farmer, the hunter, the soldier, the nanny and the doctor are all the result of an advanced civilisation built in such a way that each citizen could entrust the majority of their well-being to others. It worked because we all rely inextricably on each other. The doctor can afford to spend the time learning the complicated details of human anatomy confident in the knowledge that someone else is growing the grain, another is grinding it, another is baking it into bread, and yet another is turning it into lunch.

As trade grew and as we specialised into the many roles that civilisation required, early human civilisations also began to domesticate wild animals, such as horses and cattle, and managed to persuade them to do a large fraction of the work for us. But there were always limitations involved in using animals to drive our machinery. For a start, animals need feeding and housing, they have limited endurance and they require a great deal of space (and mucking out). Also, they have an inconsiderate tendency to die just when they’re getting useful.

So although animals became a big part of the industrial processes that drove Western Civilisation, we were also keen to harness the power of nature to help us out. Windmills had been in use since the 9th century CE, but again they were limited: they could only work when the weather conditions were right, and hence they could only work at certain times and in certain locations. They also required vast structures to be built in order to support sails of a sufficient size. Watermills had also been used since the time of the Ancient Greeks, but their use was even more limited, as they needed to be located near sufficiently powerful streams or rivers in order to function well. So non-animal power sources were available, but they were so limited that the process of generating power changed very little in two thousand years.

At the time of Isaac Newton’s death almost all work was done either by living creatures, or by the wind. But a brand new technology had begun to appear across Europe that was soon to change all of that in a
remarkable way. In 1712, fifteen years before Newton breathed his last, another Englishman called Thomas Newcomen (1664 – 1729) was introducing the world to his ‘atmospheric engine’, a device which harnessed the power of steam to pump water from flooded coal mines. Newcomen’s device built on a series of inventions by scientists from the late 17th and early 18th centuries, such as Denis Papin and Thomas Savery. It is with that same Monsieur Papin that our story begins.

Denis Papin (1647 - 1712) was a French inventor, originally a doctor, with a wide interest in physics and chemistry. He had the misfortune to be born a Calvinist at a time when the fiercely Catholic French government was persecuting those of the protestant faith, and so Papin left his homeland and spent two substantial periods in London, returning to the continent in between but avoiding places that might have seen him thrown in jail for his heresy.

Between these two stretches in which he worked in London, Papin made the mistake of studying with Newton’s greatest nemesis, Gottfried Wilhelm Leibnitz12 (1646 - 1716). Because of this innocent decision, it would not be unreasonable to imagine that Newton would have been less than cordial to the young Frenchman whenever they met. Newton was renowned for his enduring grudges, and as far as we can tell, this is exactly what happened. As far as terrifying ordeals go, lecturing in a foreign language in front of Isaac Newton and his entire retinue must have been right up there with the worst of them. But if Newton decided he didn’t much care for the company you kept, then the experience would have rapidly become an utter nightmare.

Papin had first worked in London during the late 1670s under the tutelage of Robert Boyle, investigating the effect of pressure on gases at various temperatures. Boyle’s work on gas pressure in the late 1650s had already led to the publication, in 1662, of his famous discovery on the relationship between pressure and volume of gases which today bears his name. As you squeeze a fixed quantity of gas, it decreases in

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12 Of whom, more later
volume by exactly the same proportion. If you double the pressure applied then you halve the volume. This is how SCUBA divers fit an entire hour’s worth of air into one small cylinder. However, this law only applies if you keep the gas at a constant temperature.

That last point about keeping the temperature constant was, of course, a rather important caveat. After all, if you heat up a gas then it tends to expand of its own accord, ruining Boyle’s tidy mathematical relation. This is the principle by which hot air balloons rise; because the air inside is hotter than the air outside, then it expands so that the same mass of air fills a larger volume and is, hence, less dense. The buoyancy of a gas is related to the difference between its density and that of the surrounding air. Therefore, a balloon full of hot air, which is less dense than the cold air surrounding it, will rise upwards. In fact, it will continue to rise until it reaches a height where the density of the air outside is so low that the buoyant force pushing it upwards is exactly balanced by the force of gravity pulling it down.

All this got Papin thinking. If you increase the temperature of a gas, then it naturally increases in volume – as a hot air balloon demonstrates. But what if you were to keep the volume constant, too? Well, then there would only be one possible outcome – the pressure would increase. Think about what happens when you heat water in a sealed container – eventually the pressure becomes so great inside that the container will violently explode.

It wouldn’t be until the late 1780s when the French physicist Jacques Charles (1746–1823) would first write down the precise form of this relationship: when the volume of a gas is kept constant, then every fractional increase in temperature is matched by an equal increase in pressure. In this way, for a fixed volume of gas, the ratio of pressure to temperature always stays the same. In fact, Charles put this knowledge to work as a passionate balloonist – being instrumental both in the first ever flight of a hydrogen-filled balloon, and also in the Montgolfier brothers’ legendary flight of November, 1783. And though a gap of
over a century separated Boyle’s first experiments with the discovery made by Charles, this period was not a barren one.

The importance of this new-found science of gases might not seem immediately apparent until you realise the next step after Boyle’s work, which was exactly what people like Papin worked on throughout the end of the 17th century and the first few years of the 18th century. If, by heating a gas, you can increase its pressure, then you are essentially storing energy that could later be used to do work. Think of this like blowing up a party balloon. In this case, it is your lungs that are supplying the energy to increase the air pressure inside the balloon, but the principle is the same – you have created a pocket of air at a greater pressure than the air around it, and when you let go of the neck of the balloon, that air rushes out at high velocity, propelling the balloon in the opposite direction. This is Newton’s third law of motion, of course – expelling the air in one direction causes an equal acceleration of the balloon and its remaining air in exactly the opposite direction.

So the idea seemed fairly straightforward – if you could heat up a sealed container then the contents would increase in pressure. Once you did that, then the pressurised contents could be directed towards whatever device you cared to invent that could harness the extra energy to do work. Yet all of this theorising relied on sufficiently advanced engineering knowledge so that a pressure-safe device could be constructed in which a volume of gas could be heated. It also relied on some way of releasing the pressure in a controlled manner so that it could be harnessed exactly as required, without exploding violently.

Papin didn’t realise the implications of this theory until he had left London to live in Germany around 1690. Up until that point, he had mainly been developing a series of pressure cookers, which were fitted with pressure release valves in order to protect them from a catastrophic explosion. Yet he noticed the remarkable force exerted by the escaping steam when the valve was opened, and it didn’t take him long to begin investigating how he could harness that power for constructive ends.
The Frenchman returned to London in 1707, by which time Newton was well and truly in charge of the Royal Society, and Papin had a number of prototype steam-powered devices to present. In fact, eight years earlier, the English physicist, Thomas Savery (1650-1715), had himself demonstrated a steam powered device to the very same society, which was used to pump water using an ingenious series of pressurised chambers and valves. It had no powered moving parts, but it undeniably demonstrated that useful work could be accomplished by the use of this new concept of “steam power”.

Papin fared rather worse than most of his contemporaries, and I’m afraid his own story does not end well. After five long years in London, trying in vain to obtain some recognition for his discovery, he died in poverty in 1712. The exact date of his death is not known, and neither are the whereabouts of his final resting place, which seems a thoroughly unsuitable end for such an important figure, dumped unceremoniously, historians assume, in a pauper’s grave. A sad end for such an influential scientist, and I’m afraid it’s not the first such story you will hear before the Epilogue. I feel it’s my duty to shine a light on some of these forgotten heroes, partly to demonstrate that it’s not just the famous names whose contributions have lifted us up towards the modern world.

However, after Papin’s death others took over his research. In the very same year, Thomas Newcomen produced a suspiciously similar contraption, the celebrated atmospheric engine that I mentioned earlier, which used steam power to pump water from mine shafts. Newcomen’s device was substantially more advanced than Savery’s pump of 1699, providing a much more constant and useful source of power, rather than a single dramatic burst. Thanks in no small part to Papin’s discoveries, Newcomen fitted his steam engine with a piston which moved upwards as steam expanded into a pressurised chamber. The piston drove a rocking beam, which was connected to a mechanical pump, making the engine ideally suited for removing water from coal mines.
Newcomen’s engine brought the financial success that both Papin and Savery had failed to obtain. Savery, however, had taken the trouble to patent his own invention, and due to the similarity of Newcomen’s creation he ensured himself a steady income. Pumps were sold across Great Britain and, eventually, across much of Western Europe, and the success of the design continued until well after the deaths of Savery in 1715 and Newcomen in 1729. In fact, although the Newcomen engine was a highly complicated, inefficient and expensive piece of machinery, it would still be half a century before anyone managed to improve on it.

It seems like an overstatement, but when someone did finally improve on Newcomen’s first industrial-scale steam engine, the revolution caused by this new found source of power ushered in what could easily be described as the greatest social upheaval ever to affect the civilised world. This one invention alone justifies the inclusion of ‘steam power’ as the second of the great discoveries that I want to describe in this book. You see, steam power gave us a huge number of technological benefits that we still use even today, but it also provided us with something more – it gave us the ability to take an extraordinary social leap which would forge a new age of prosperity and productivity. Furthermore, it would revolutionise the way we saw our individual roles in society, and it would bring us one step closer to each other, binding us yet tighter together and on an even larger scale than ever before.

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James Watt was born in 1736, a mere nine years after Isaac Newton’s death. His name is perhaps the one most closely associated with the development of the steam engine and its eventual adoption in the mills and factories of the Industrial Revolution, though his work built heavily on those discoveries that we have already met. Watt’s modifications to Newcomen’s design allowed for far greater efficiency and power by a cunning separation of the condenser and cylinder in the central engine. This gain in efficiency, allowing the pump to work with less than a quarter of the amount of coal required for Newcomen’s device, proved
crucial, and Watt’s engine was set to revolutionise the generation of power for almost two centuries.

Watt was a brilliant engineer, and was also a prominent member of the Lunar Society – a renowned group of intellectuals living around the Birmingham area in the 18\textsuperscript{th} and 19\textsuperscript{th} centuries, founded to inspire the investigation of scientific principles. In the absence of institutionalised academic research, much of the most important scientific investigation was undertaken by enthusiastic amateurs, meeting regularly to discuss matters of science and, it can hardly be denied, profit. Amongst the occasional members of the Lunar Society were such internationally renowned minds as Benjamin Franklin (one of the founding fathers of the United States), Matthew Boulton (James Watt’s wealthy business partner), William Herschel (the famed astronomer), Josiah Wedgewood (of pottery fame) and Erasmus Darwin (a celebrated doctor, and Charles Darwin’s grandfather).

From these illustrious names, William Herschel (1738–1822) is of particular relevance to this book, as he made a number of discoveries across a range of topics in the science of Astronomy that directly related to Newton’s most famous theories. For a start, he discovered the planet Uranus – the first planet to be discovered with a telescope, as it is far too faint to be visible with the naked eye. Herschel also measured the planet’s orbit, and confirmed that it was in agreement with Newton’s laws of gravitation. Using a telescope that he built himself, Herschel went on to discover the moons of Saturn and carried out the first ever analysis of binary star systems - where two stars orbit each other closely - proving for the very first time that Newton’s laws of gravitation applied outside our own solar system.

Herschel was also the first to describe the discovery of infra-red radiation, further extending the work on the nature of light that Newton began in his darkened college room. He discovered that the Milky Way galaxy was disk-shaped, and he coined the term “asteroid”. However, just like Newton, Herschel wasn’t immune to wild speculations – he
was convinced that the interior of the Sun was a solid planet just like Earth, inhabited by alien creatures with enormous heads. But hey, nobody’s perfect.

Herschel ranks as one of the foremost astronomers of his, or indeed of any time. Any one of the discoveries I just listed would have been enough to guarantee him immortality in the annals of science, but yet he discovered them all. And what’s more, he did so without great wealth, without the economic incentives that drove people like Newcomen and Watt, and without the global recognition that someone like that would doubtless receive today.

So the eighteenth century marked the first time men really started making fortunes through science, but the research was still being carried out the same way it was in Newton’s time – by those who had an obsessive passion for knowledge, and were willing and able to dedicate their lives to its pursuit. One could argue that it was also the last age of the ‘gentlemen scientists’, as the enthusiastic amateurs began to give way to those with more considerable resources. Characters like Herschel, who earned his wages as an accomplished professional musician and composer for much of his life, were a dying breed. Science was getting harder, and with the dwindling patronage of the aristocracy and royalty, together with the increasing complexity and expense of the necessary scientific instruments, the established way of doing things was about to change for ever.

The industrial revolution was largely driven by capitalist pressures and incentives. Watt, thanks to the extraordinary value of his discoveries and the business sense that he had managed to develop, died a very wealthy man at the healthy age of 83, in 1819. He had amassed his fortune by supplying the finest steam engines in the world for over twenty years, practically unchallenged. His first installations had been pumping engines for mines, especially valuable in parts of the world where coal was expensive. Though the machines were not cheap, the savings to be made by Watt’s efficient design were often substantial.
Later, Watt, together with Boulton, built and sold engines to all manner of businesses, including the factories and mills which formed the heart of the industrial revolution.

At the other end of the wealth scale, the industrial revolution was also causing enormous social changes. With advancements in farming, it was now possible for a far smaller number of farmers and rural workers to generate enough food to feed a growing population who wished to work in the rapidly growing cities. Because of this increase in productivity, caused in no small part by scientific advances over the preceding century such as Jethro Tull’s seed drill of 1701, production was moving away from village industries towards urban centres. Instead of growing up in the fields, children were now being sent to work in dangerous conditions in cotton mills, sometimes from ages as young as four. Many did not survive, and those who did often suffered from respiratory conditions caused by the filthy and dangerous environments in which they were forced to work.

I think it’s fair to say that this extraordinarily rapid scientific progress definitely had its negative side. In the early 19th Century, disgruntled textile workers formed an organisation called the Luddites, who attacked and destroyed weaving machinery in a protest against this disruptive new technology. The elaborate weaving machines, which required relatively little skill to operate, were rapidly making the Luddites’ own painstakingly-earned skillset obsolete. They urged, often backing their threats by the use of violence, that textile manufacturers abandon these new, threatening technologies and return to the delicate manual labour that they were so rapidly replacing.

The Luddites’ attempts to drag Britain back to the “good old ways” of manual labour echo a trend that has happened many times in the history of the advancement of science, and continues today. In the 21st Century, we can see the same problem with advocates of physical 20th Century

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media such as compact discs, DVDs, books and newspapers rapidly and angrily losing the inevitable war against digital distribution. In fact, one of the first examples of this process happened in the 15th century in a closely related field.

The arrival of mass production in the Industrial Revolution, though remarkable, was not the first time it had been seen. In the mid-fifteenth century the German printer Johannes Gutenberg (1398-1468) built his first printing press using movable type, which increased the output of a single printer by roughly one hundred times, or a thousand fold over that of a single scribe with pen and ink – rapidly making those latter tradesmen rather redundant. Though books were still extremely costly, they were no longer merely the prize of royalty – they could at least now be afforded by smaller institutions, and over the subsequent centuries their price would come down much more drastically as printing presses based on Gutenberg’s first prototype spread throughout Europe.

The revolution caused by the invention of the Gutenberg press was perhaps most keenly felt in religious circles. Gutenberg himself printed thousands of ‘indulgences’ for the Roman Catholic Church in the years 1454-5 – a kind of contract that worried sinners could purchase in order to be partially absolved of their Earthly misdemeanours. The church then sold vast numbers of these to its guilt-ridden adherents in a giant “Cash for Forgiveness” scam. Then in 1455 Gutenberg printed 180 copies of his famous Bible – an astoundingly beautiful work of extraordinary complexity, which surely ranks as one of the greatest wonders of human ingenuity. Sadly, only 21 copies survive complete to this day, and those extraordinary books are unsurprisingly worth a fortune, not just because of their historical importance but also because of their intrinsic beauty as works of art.

Even though the full print run of the Gutenberg bible sold out almost immediately, Gutenberg himself was declared bankrupt a few years later, and died penniless and unrecognised in 1498. This may seem
familiar to those of who were paying attention to the sad story of Denis Papin earlier on. Often it is not the first trailblazers who get the wealth and recognition in their own lifetimes, though they usually receive their deserved honours much later. After all, Gutenberg’s primary investor, Johann Fust, seems to have died a very wealthy man, but who remembers him?

Given the money they made from Gutenberg’s indulgences, one might think that Gutenberg’s contribution had been a positive one for the Roman Catholic Church, but the story is not yet over. A few decades after his death, Gutenberg presses all across Europe were used to print an estimated 300,000 copies of German theologian Martin Luther’s ‘95 Theses’ denouncing the Roman Catholic church and marking the start of the Protestant revolution, which culminated in Britain in the 1530s when Henry VIII separated formally from Rome and set up the Church of England.

The invention of high-volume printing also led to the sale of the Bible in the English language, with the celebrated King James version, first published in 1611, which would have been the one used by Newton in his studies. The wide availability of cheap English language Bibles, together with the increased literacy that it fostered, further destabilised the influence of the priesthood as it partly removed their monopoly on religious interpretation and allowed the general public to read and understand the words directly and make up their own minds as to what they meant.

The whole process of industrialised printing made possible the publication of Newton’s celebrated work, *Principia Mathematica*, of course, but its role in the foundation of a scientific establishment went much deeper. Without the dissemination of knowledge, there could be no collaborative research, no peer review, and no organised debate. And without those components, the scientific community could never have been founded.
Despite a steady stream of highly incentivised innovators and mechanics, it took three-and-a-half centuries after Gutenberg’s first press to double its rate of output. Charles Stanhope’s cast iron printing press of 1800 could churn out books at a rate of almost 500 pages per hour, but this was merely a foreshadow of the progress that would follow over the subsequent two decades, triggered by the invention and proliferation of cheap steam power. By 1820, steam-powered presses based on the work of German-born engineer Friedrich Koenig had increased this rate another five-fold. The first mass-produced newspapers were becoming a reality, delivering news and opinions to a previously under-educated and mostly illiterate lower class.

So steam power didn’t just catalyse the industrial revolution, it also ushered in a new and more subtle revolution – the ubiquitous, Internet-fuelled mass media that we enjoy today have their roots in the work of the pioneers of printing throughout the early 19th century. The process of democratising knowledge, which began with Gutenberg’s first press in Mainz in 1440, was a key feature of the development of the entire scientific edifice. Mass printing gave us not only cheaper and more readily available books, but it also standardised texts – no longer did you have to trust (and pay) a single scribe to copy out a book by hand, introducing plentiful errors (both deliberate and accidental) along the way.

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Even though the developments of steam power had been revolutionising the way people worked across Europe, progress was also beginning in many more theoretical areas of study during this time. The years following Newton’s death saw a plethora of activity, primarily in the mathematics that were now required in order to build the framework for the steady stream of discoveries that were flowing from scientific institutions across Europe. People like Gauss, de Moivre, Poisson and Bernoulli formalised the field of mathematics that we still use today to test 21st Century scientific hypotheses.
Another contemporary and staunch defender of Newton’s ideas was the Presbyterian minister Thomas Bayes (1701-1761). Though he worked in several different fields in his lifetime, Bayes is probably best known for his contributions to the scientific theory that Newton was beginning to formalise. Bayes’s work answered a substantial chunk of that second fundamental question of science, only incompletely answered by Occam’s razor (the concept that “simple is best” that we met in the previous chapter). That second question could be summarised like this: “How should the things we see in the world affect our opinion of the scientific laws underlying them?”

Bayes’s work has been used for a huge range of applications, though its fundamental importance is in understanding the way in which we can combine evidence from many different observations to give us a picture of the relative likelihood of a range of proposed models. Bayesian thinking transformed science from the work of a few isolated geniuses, each meddling in their own fields of interest, into a process capable of building a framework of knowledge for the entire human race. It was the key idea with which the research community could start using science to create a solid base upon which they could build increasingly elaborate theories and models, and against which any new theory could be judged.

All ideas are not born equal. Bayes went a step further than Occam’s Razor and developed a way by which we could compare any two proposals, regardless of the assumptions they made, and the evidence in support of them. What Bayes realised was that ideas should not just be assessed based on evidence directly gathered in their support (what we might call “evidence-based investigation”), but that we also need to consider any claim in the light of our prior knowledge, too.

Needless to say, and much as it might not seem so from that previous paragraph, it’s a concept that we’re all rather familiar with. Let’s say I’m out one day, minding my own business, walking down the high street, and I glance across the road to the other side where, to my
amazement a fantastic sight catches my eye: striding amidst the crowds before me, I can clearly see a man who looks exactly like Elvis Presley. Now, this man is precisely the right height, he has Elvis’s hairstyle, he’s dressed in Elvis’s clothes, he has “Elvis” written on his back in sequins, and he’s carrying a guitar case. All the evidence gathered by my senses is telling me that I am in the presence of The King.

So this is where Bayes joins the story. What Bayes formalised was the obvious caveat to my otherwise flawless deduction, namely that we have other knowledge that we must bring into this scene. Although all the evidence taken during my ‘experiment’ seems to confirm the conclusion that Elvis is alive and well, and just walking into the local Post Office, we also have the prior knowledge that Elvis Presley died in August 1977. Now, what this tells us is that the figure that I saw could not possibly be Mr Presley, but merely an off-duty impersonator.

Strictly speaking, what Bayes’ theory tells us is that, were we to conclude that I had really seen Elvis Presley with my own eyes, then we would need evidence so overwhelming that it explained away the near-universal agreement that he has been dead for decades; it would also need to explain away the fact that this alleged ‘Elvis’ still looked to be in his mid-thirties, and not an elderly pensioner, born in 1935.

So, strictly speaking, even though my chance encounter was overwhelmingly likely not to be with the real Elvis Presley, Bayes’ theorem doesn’t rule it out entirely – it merely shows me that I would have a great deal of work to do if I wanted to prove I had met the King. Bayes’ theorem doesn’t dictate absolute and unalterable truths – Science rarely does this, though there are some theories in Science that are so overwhelmingly likely that I can’t imagine how they could ever be disproved. I don’t expect to wake up tomorrow and find that gravity isn’t working, for example. What Bayes’ theory does do is tell us what kind of evidence we would need to provide in order to prove absolutely anything, regardless of what we currently believe to be true. More importantly, it tells us how confident we can be about our existing
conclusions. If you like, it places theories on a “spectrum of certainty”, from “extremely likely to be true” at one end to “extremely likely to be false” at the other.

This may seem like an obvious discovery, and perhaps it is to our 21st century eyes, but it’s often woefully ignored, even today. Carl Sagan, perhaps the greatest ever populariser of science, put it this way: “Extraordinary claims require extraordinary evidence”\textsuperscript{14} Sagan wrote a great many books, several of which should be required reading for all of humanity. In perhaps his best loved work, \textit{Demon Haunted World}, he talks about how science decisively combats superstition and fraud. Bayes’ theorem is a fundamental part of the arsenal with which it accomplishes this. Yet still people discard all that we know about the physical Universe because they hear one convincing salesman with an ‘honest looking face’ and an intriguingly expensive perpetual motion device...

The story of the industrial revolution, kick-started by the work of pioneers such as Papin, Newcomen and Watt, shows both sides of the scientific coin. The undeniable prosperity and power that these advances provided, together with the extraordinary increase in the dissemination of knowledge through steam-powered printing presses, underpinned the modernisation of society and brought affluence to millions. But it also brought about social shifts which, for a substantial fraction of the population, meant a change in the way of life that their ancestors had followed for centuries, and not always for the better.

Steam power revolutionised the course of human civilisation, but one of the most profound developments that it brought is more fundamental: steam power hugely advanced the separation of mankind from the natural processes on which we had been so dependent for so long. Now that human beings could create their own power wherever and whenever they liked, they were no longer constrained by geography or

\textsuperscript{14} He first said this as part of his TV series “Cosmos”, episode 12, though it has since become something of a mantra for the Scientific Skepticism movement.
weather over which they had no control; nor over the limits of their own muscles or physical health, or of their beasts of burden.

The minds of human scientists had, in a very real way, become vastly more productive than the strongest and hardest-working labourers and workmen of years gone by. Printing presses powered by steam were producing tens of thousands of pages per day, when a scribe could produce only a handful. Those presses were distributing knowledge to the masses; they were printing great works of literature, newspapers and dictionaries. They were the very engines of social progress throughout the 19th century.

Technology allowed for a new scale of productivity now that the rate of production of society was not limited by the size of its workforce, but by the intelligence of its inventors. And, as it turned out, Britain had some astoundingly bright inventors. The Industrial Revolution, fuelled quite literally by Britain’s copious reserves of coal, propelled the nation to the forefront of international power and glory, with an empire that spanned the globe.

More than that, the discovery of steam power could be said to have contributed to the end of one of the most disturbing periods of the history of Western civilisation – that of the transatlantic slave trade. Until the invention of safe, efficient steam power, the only way to get more work done was to hire (or buy, or kidnap) more workers to do it. But now there was another way, and this new technology helped to put an end to that most horrific of practices. As far as social changes go, that one was a pretty big deal.

Yet the natural world still held one highly lucrative secret that was fated to surpass even the mighty steam engine. This enigmatic pursuit excited a number of great minds, including some of the same scientists we have already met in this chapter. And yet again, the discoveries of science were set to radically reshape our view of the physical Universe and
provide another invaluable rung on the ladder of human technological achievement.

And that is the topic of the next chapter.
Immortal, Invisible

“The main Business of natural Philosophy is to argue from Phenomena without feigning Hypotheses.”
Newton

During the extent of the Aztec civilisation in South America between the 14th and 16th centuries, it has been estimated that as many as a quarter of a million citizens were slaughtered every year in brutal sacrificial ceremonies aimed at appeasing the capricious gods of nature. Those gods, it seems, had a particularly fond taste for the internal organs of the Aztec people, refusing to allow the rains to water any crops until their sadistic desires had been appeased by cascading torrents of human blood and piles of severed hearts. Or so the legend goes.

The Aztecs blamed, or rather cursed, their gods for nearly every natural affliction that ever affected them, from floods to droughts, from great storms to earthquakes and volcanic eruptions. In order to propitiate these angry deities, the high priests would plunge their ceremonial daggers into the chests of their victims, slice out the heart, and then decapitate the bloodied corpse. And they would do this seemingly without tiring, hour after hour, for days, weeks, even months at a time, as the blood flowed from their altars and down the steps of their majestic pyramids.

Hernán Cortés, the Spanish Conquistador, describes such an event in his Letters.

They have a most horrid and abominable custom which truly ought to be punished and which until now we have seen in no other part, and this is that, whenever they wish to ask something of the idols, in order that their plea may find more acceptance, they take many girls and boys and even adults, and in the presence of these idols they open their chests while they are still alive and take out their hearts and entrails and burn them before the idols, offering the smoke as sacrifice.¹⁶

What sort of conditions could drive a human being to do this to their fellow citizens? Why were otherwise intelligent people willing to slaughter thousands upon thousands of their kin seemingly without remorse or self-doubt? The great Aztec empire possessed extraordinary architectural capabilities, elaborate arts and poetry, compulsory formal education, complex economics and a capital city over twice the size of London at the time. One can’t help but wonder what might have happened to them were they to have abandoned this self-destruction, and instead devoted their energies to understanding and harnessing the weather, instead of trying to control it with futile and morally abhorrent propitiatory genocide.

Yet it is human nature to seek out a cause for everything that we cannot understand, especially when that event threatens our livelihoods. We fool ourselves into believing that we understand those things that threaten us, because once we understand them we might be able to change them. So once we convince ourselves we know what’s going on, we can do something that we believe will help. And, regardless of whether our actions are helpful in any way, the belief that they are is usually enough to calm our fears.

¹⁶ Hernán Cortés, Letters, 1523.
This same fervour whipped the Aztecs up into a bloodthirsty frenzy where millions of citizens were sacrificed to appease imaginary deities, claimed to control meteorological events that we now know are fully dictated by air pressure, sunlight, evaporation and condensation. But the Aztec empire grew without any of this modern scientific knowledge, and huge disasters demanded immensely powerful causes. And what could be more powerful than a god?

Since early times, inclement weather has been associated with a bewildering pantheon of angry deities. The ancient Egyptian Sun god, Amun-Ra, possessed control over the fiercest tempests; The Norse people worshipped Thor, the mighty god of storms; The Greeks and Romans worshipped Zeus or Jupiter, the sky-god who wielded the thunder and lightning granted to him by the Cyclopes. In the Hebrew Bible, the Jewish god Yahweh caused the heavens to open and rain to fall for 40 days and 40 nights, flooding the entire Earth and wiping out all but eight of its human inhabitants. Early civilisations were very much frightened by the great power of nature, and could only understand it by ascribing it to some unseen agent, angry, violent, capricious and intent on unleashing his fury on the slightest whim.

Even in the 21st century, weather still retains a capacity to terrify. Tropical storms kill thousands of people every year across the world, and tornados strike with random violent devastation, especially in North America. The less dramatic climatic conditions – drought, for example – actually kill many more, especially in sub-Saharan Africa. Even though we now understand how all of these phenomena arise, there is still a certain terror in knowing that we have almost no control over them. In fact, were it not for the reassuring methods that scientific ingenuity has given us to cope with the harshest extremes of the natural world, it might be even more terrifying to understand our abject helplessness in the face of mother nature’s powerful grasp.

Human beings had no doubt marvelled at the phenomenon of lightning for thousands of years before it occurred to one man, Benjamin Franklin
(1706 - 1790), that perhaps the destructive power of nature could be harnessed, and therefore that it should be studied and understood instead of feared. I’m sure that the story of Franklin’s experimentation is well-known to many of you, though the details have been embellished over the years, as storytellers often do, to add extra heroism and drama.

Franklin, one of the pioneers of the modern science of electricity, shared Newton’s reckless disregard for his own health in pursuit of knowledge. He wrote of his hypotheses regarding the nature of lightning in the late 1740s and in 1750 published some thoughts suggesting that it might be possible to force lightning to strike a point of his choosing during a lightning storm, by raising some kind of conductor high above its surroundings. Initially Franklin had suggested that this feat be attempted from the spire of Christ Church in Philadelphia, which was under construction at the time, though the construction proceeded rather slower than had been expected, and Franklin grew impatient.

As it happens, contrary to the legend, it appears that Franklin was beaten to this rather reckless act. On May 10th 1752, Frenchman Thomas-François Dalibard did precisely what Franklin had suggested, using a 13 metre tall iron rod instead of a steeple, and was able to measure the build-up of electrical charge in the rod. A few weeks later, in June 1752, Franklin gave up waiting for the church steeple to be completed, and decided to duplicate the experiment using a metal key attached to a kite string. They key was in turn attached to a device known as a Leyden jar, which was used for storing electric charge. Though the kite was never actually struck by lightning, Franklin was able to measure a build-up of electrical charge in the jar, and thus proposed that lightning was indeed an enormously strong electrical discharge. The story of Franklin clinging on to a metal key and frying himself during a lightning strike doesn’t appear to bear any relation to actual history, I’m afraid.
By the way, Franklin never actually coined the term “electricity” – he merely helped to develop some of the theory behind it. The term itself comes from one and a half centuries earlier, due to a largely unknown English scientist named William Gilbert (1544–1603). Gilbert was the President of the Royal College of Physicians, and the personal physician to both Queen Elizabeth I and King James I, for a few short months until his death.

One of Gilbert’s more intriguing interests was the study of blocks of amber, and particularly the bizarre effects that he could cause when he rubbed those amber blocks with a piece of fabric. It had been known for many centuries that under these conditions the amber would attract lightweight particles of fabric or dust towards them. It’s exactly the same feat that we nowadays demonstrate by charging up party balloons on our woollen clothes and then holding them near a friend with long hair. Gilbert theorised that the rubbing removed some layer of a hitherto unknown substance or ‘effluvium’ from the surface of the amber, which renewed the attraction effect within the substance. Amber, in Greek, is elektron, so Gilbert named this force the electric force. It was not until 1646 – when Newton was four years old – that Sir Thomas Browne (1605 – 1682) coined the term “electricity” to refer to the general property of an object to exhibit this electric force.

Gilbert’s work compared the effects that he could generate with amber, with the properties of naturally magnetic substances. From his painstaking observations, he concluded that electricity and magnetism were two very separate forces, despite their similar effects when measured in the laboratory. He performed a number of experiments designed to demonstrate this fact – which is unfortunate, as we now know that he was essentially incorrect. Although, in his defence, it would be more than two centuries before James Clerk Maxwell (1831-1879) realised that magnetism and electricity were in fact manifestations of the same underlying physics, and the science of Electromagnetism was released into the world.
Electricity captured the public imagination because it was an entirely invisible force – like Newton’s gravitational force. Before Newton, the idea that a force might act invisibly at a distance was deeply concerning, and the concept of action at a distance seemed miraculous when Newton first proposed it. In fact, Newton himself had a lot to say on the subject. He was adamant that such a force must be controlled by a physical substance of some kind, rather like how an elastic band might pull two objects together if they are pulled apart. Indeed, in his correspondence, writing to the Master of Trinity College, Richard Bentley, he admitted:

“That Gravity should be innate, inherent and essential to Matter, so that one body may act upon another at a distance thro' a Vacuum, without the Mediation of any thing else, ... is to me so great an Absurdity that I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it.”

Newton, it has to be said, had a habit for stating his case rather more powerfully than perhaps he ought to have done. And more intriguingly, although Newton believed very strongly that there must be some kind of substance pulling together bodies under gravity, he never advanced any opinion for what this mysterious physical medium might have been. One could say that this was the most substantial hole in his argument – and it was a considerable weakness, though it perhaps says something for Newton’s self confidence that he was able to convince himself of the correctness of his theory of gravity without fully understanding its underlying mechanism. He was not the first great scientist to achieve this feat, as we shall learn in a later chapter.

The same problem of invisible action at a distance also applied to electricity, as we have seen. Though in this case it could be argued that the problem is much simpler, because at least nobody was suggesting that the electric force applied to planets. Well, not so fast… actually, they were. William Gilbert himself was one of the first to propose the
idea that the Earth itself was magnetic, that it had an iron core, and that compasses align with the Earth’s magnetic field. It was an extraordinary claim, but it was one that would be confirmed experimentally and theoretically in later generations.

Still, at least speculation about the electric effect stayed on Earth, though it took a remarkably long time before any serious thought was made into how this effect might be harnessed for the benefit of humanity, rather than just as a novel parlour trick. Most industrialists were concentrating on the incredible gains made by the rapidly expanding steam power revolution, and so far electricity was little more than a scientific curiosity. After all, it was not obvious how such a weak ‘toy’ force such as that exhibited by amber blocks could be turned into any kind of useful machine.

And so we return to Franklin who, though he was not quite the lone genius that history seems to have remembered, was still a powerful voice in the development of electricity as a phenomenon that could be harnessed for more than just curiosity value. And, to be fair on him, he did have other things on his mind later on in his life like, oh, founding the United States of America. But nonetheless, Franklin had an active mind, and he speculated that the effect Gilbert generated by rubbing cloth across blocks of amber, might be due to the same underlying principles as some of the most dramatic and energetic displays in all of nature. If the same electricity that caused tiny flecks of fabric to dance around a charged rod could also cause lightning strikes that could cleave fully-grown trees in half in the blink of an eye, then it was a force that he needed to understand.

Franklin’s investigations into electricity did turn up plenty of new ideas. For a start, once he discovered that lightning was just an enormous electric discharge, it was possible to apply some of the studies that he had conducted in the safety of his own house, to design the world’s first ever lightning conductors, which could be placed on top of tall buildings in order to capture the energy from the lightning strikes and
divert it harmlessly away from the building itself and into the ground. The investigations of Franklin and those like him who studied lightning as a natural scientific phenomenon, ironically did far more to save the church steeples of North America than the repeated petitions of their parishioners. It is perhaps a reversal of the fate of the Aztecs – with scientific investigation coming to the defence of the established religions to protect them from the visitation of divine wrath.

Franklin notoriously didn’t have a great deal of interest in organised religion, though he was a religious man and possessed strong opinions about the link between religious beliefs and morality. One might imagine that he and Newton would have got on rather well had they ever met, at least in this regard. Newton’s unorthodox religious beliefs, though largely kept under wraps, were probably not entirely secret, and it seems unlikely that Franklin would have strongly objected to them. Unfortunately this meeting was never to be, though Franklin was indeed in London during the last few years of Newton’s life. When organising the distribution of his pamphlet “A Dissertation on Liberty and Necessity, Pleasure and Pain”, Franklin mentions that he met a certain Dr Henry Pemberton at a Coffee house in London “who promised to give me an opportunity, some time or other, of seeing Sir Isaac Newton, of which I was extremely desirous; but this never happened”

Dr Pemberton was a noted physician, fellow of the Royal Society, friend of Newton’s and the editor of the third edition of Newton’s masterwork Principia Mathematica, which was finally published a year before Newton’s death. One can only speculate about what the two great men – Franklin and Newton – might have discussed were they ever to have met. Perhaps Newton’s insight might have inspired the young Franklin to dedicate more of his life to science and less to politics – whatever that would have implied for the political future of the American continent.

17 The Autobiography of Benjamin Franklin, Ch. 5.
Franklin’s investigations into the science of electricity certainly made a number of great advances, but he never got as far as attempting to harness it. Indeed, having seen the power that electricity could deploy in a violent lightning storm, it must have been somewhat sobering to imagine any human ever wielding such a potent destructive force. The first man to harness this potential, I imagine, must have felt rather like the first man ever to consider riding a horse – that there was an enormous amount of scarcely understood power over which we had an all-too tenuous control. But were we ever to tame that power, then it could be directed for the enormous benefit of humanity.

And of course, inevitably, electricity was gradually tamed by a succession of pioneers whom we largely remember today by their surnames, which have provided us with many of the most well-known terms in electric theory. Alessandro Volta (inventor of the battery, and from whose name we derive the unit of electric potential, the Volt); Luigi Galvani (the discoverer that nerve signals in living creatures are transmitted by electrical impulses, and from whose name we get the word “galvanise”); André-Marie Ampère (founder of much of electric theory, whose surname is now the international unit for electric current); Charles-Augustin de Coulomb (who formulated a law explaining how electric charges attract and repel each other, analogous to Newton’s law of gravity. His name is given to the unit of electric charge); And, last but by no means least, Michael Faraday, whose name is now used to denote the unit of capacitance – the ability of an electrical component to store an electric charge. For some reason, he lost a couple of letters, to create the ‘farad’.

In fact, in the interests of brevity, I must sadly forward-wind past some of the build-up to the human taming of electricity, and skip straight to that same Michael Faraday (1791 - 1867), whose story continues our tale. And he is a particularly clear choice for the next step in this journey because he was the figure who brought together all the threads of understanding in the early- and mid-19th century – in much the same way that Newton had done with the work of Copernicus, Kepler and
Galileo on planetary motions – to build up a coherent picture of electricity that would be reasonably close to the one we understand today. And Faraday, like Newton, was a prominent member of the Royal Society, continuing that tradition for academic excellence into the 19th century. Though unlike Newton, Faraday refused the offer of becoming its president. Twice.

This whole electricity fad was all rather exciting, and it certainly occupied a great many brilliant scientists, but so far it hadn’t really produced very many perks for the general public. Except those who happened to own houses with steeple, that is. Yet there was an obvious question to ask about this new force, which Newton’s colleagues had been asking roughly a century later, and that was: how can we turn this powerful force into useful energy? In short, how can we harness electricity to make an electric engine, just like we harnessed steam power to make a steam engine?

Well the first person to answer that question conclusively was indeed Michael Faraday who, in 1821, succeeded in creating a simple, yet functional electric motor. It was hardly a motor as we would recognise today – really all he achieved was to show how a length of wire could be forced to move continuously in a loop, suspended in a container of mercury. The power delivered by this contraption was negligible, though it was proof enough that electricity was very much more than an intriguing parlour trick. On the contrary, this previously misunderstood, invisible property of certain substances could, at least in theory, be harnessed to create motion.

After Faraday’s discovery, the rest was really just an exercise in scale: how could we generate more of this electricity to drive motors and similar contraptions, and how could we build this up to useful levels of power? And again, it was Faraday who discovered the principle of induction in 1831, and hence produced the first ever electric generator.
The principle of the generator really isn’t that different to that of the motor – in fact, it’s basically just a motor running in reverse (using motion to generate electric current, rather than using current to generate motion). Faraday wrote down this relationship in his famous law of induction, which stated that the amount of electricity generated in a generator was related to the total flux of magnetic field through a conducting loop.

To imagine this, you may find it helpful to think of the magnetic field lines from a bar magnet like visible strings. Imagine that these strings shooting out from one pole of the magnet, loop around in a big arc, and stick back into the other end of the magnet. You may have done the experiment at school when you cover a bar magnet with a thin sheet of paper and sprinkle it with iron filings to view the field lines. Anyway, the lines look something like Figure 2.

![Fig. 2: Magnetic Field Lines. Image: Wikipedia.](image-url)

Now the flux through a loop of wire is proportional to the number of those field lines that go through the loop. And Faraday said that the change in this quantity was what caused the generation of electricity. So if you spin the wire round the magnet then you are causing a change in magnetic flux, and therefore generating a current in the wire. And Faraday realised that the best way of generating the greatest quantity of magnetic flux was to coil as many loops of wire as possible inside his generator, and then spin it extremely quickly. And in this case the relationship is simple – twice as many wires generates twice as much...
electricity. Spinning the coils twice as fast also doubles the electrical current generated, because you’re changing the field through the wire loop twice as quickly.

If you can picture this device then you basically understand how generators work even today, in most types of power station. All you need is some way to turn a loop of tightly-wound coils of wire through a magnetic field. That is usually achieved using a turbine. In a windmill of a hydroelectric power plant the link is straightforward, with the turbine spun by wind or water and directly driving the generator. In a coal-fuelled power station, the coal is burned, which heats water, which is converted to steam. That steam builds up pressure, is forced through a turbine, and finally drives the generator. It is a process that Faraday would easily understand, were we to pick him up from the 19th Century and push him forward to today. But it would have seemed utterly alien to Isaac Newton.

So what had changed in physics over those hundred years between the death of Newton and Faraday’s two great discoveries in the use of electrical power? The work completed by Faraday triggered a revolution rather like the one Newton brought about for the concept of gravitational force. Scientists had been marvelling at lightning since the dawn of the human race, and they were also well aware of naturally magnetic substances, which had been known since antiquity. Thales of Miletus (c. 624BC – 546BC), regarded by many as the first ever professional philosopher, was perhaps one of the first to experiment with static electricity, using rods of amber. Certain creatures like electric eels could generate powerful shocks underwater, and scientists like Galvani, whom we briefly met earlier, had already started wiring dead animals into electric circuits to demonstrate that living creatures were powered by a kind of electrical energy. Newton would have been aware of all but the latter of these, and his keen practical skills, albeit never really honed on animal subjects, would readily have demonstrated the effect that made Galvani famous.
What Faraday did, however, was to set the seeds for a synthesis of all of this knowledge. These many different effects were well known and well-studied, but nobody suspected that the exact same underlying physics was responsible for every single one of them. These diverse effects were thought to be caused by different types of electricity, but Faraday realised that this was not the case – it was the exact same physics underlying all of these different processes. And that’s exactly the same realisation that Newton made when he replaced Aristotle’s notions of many different natural processes, all caused by complex relationships between fundamental natural elements like earth and water, with one single law of gravity with a single property, mass. Just as Newton’s law was exactly the same for apples, rocks and cannonballs, for planets and stars and all other bodies in the Universe that have mass, so Faraday’s discoveries, and the more mathematical formulations of James Clerk Maxwell (1831 - 1879), who followed him, showed that electricity and magnetism are manifestations of the same underlying process, and that it applies equally to all the many examples of electricity that we had already observed. The same power that surges through a mighty lightning strike, shattering a tree trunk into splinters and igniting raging infernos, is the same power that flows through your brain, and indeed flowed through the brains of the greatest scientists who ever lived. One invisible force brings both destruction and understanding.

Given the extraordinary developments that this breakthrough has facilitated since Faraday’s time, it was still quite a while before electric power overtook steam power for all practical purposes. In fact, for the early uses of electricity, the major selling points seemed to be in fields where steam power had little to add, such as communications and lighting. When William Gladstone, the British Chancellor of the Exchequer and later four-time prime minister, asked Faraday in 1850 what on Earth the practical value of this new knowledge might be, Faraday’s answer showed his sense of humour as well as his canny
knack for understanding the forces that drive human endeavours: “One day sir,” he replied, “you may tax it.”\textsuperscript{18}

Of course, that is exactly what happened. And though electricity developed over the following decades in many ways that even Faraday would never have predicted, the science behind it barely changed from those simple laws laid down in the 19th century. In fact, writing 6 years after Faraday’s death, Faraday’s successor James Clerk Maxwell – the man perhaps more synonymous with understanding the science of electricity and magnetism than any other figure in history, had this to say or his illustrious predecessor:

“To estimate the intensity of Faraday's scientific power, we cannot do better than read the first and second series of his Researches and compare them...with the whole course of electro-magnetic science since, which has added no new idea to those set forth, but has only verified the truth and scientific value of every one of them.”\textsuperscript{19}

Around the same time that Faraday was making these discoveries, William Whewell (1794 – 1866) was Master of Isaac Newton’s Alma Mater, Trinity College, Cambridge. Whewell was one of the great figures we encountered a few chapters back in the Introduction, immortalised for all time in stone at the entrance to the Chapel of that illustrious place of learning. And with good reason. Though not directly responsible for the science behind Faraday’s discoveries, he was responsible for much of the terminology, including the terms “anode” and “cathode” for the terminals from which electric current flowed into an electric circuit, and towards which it flowed out, respectively.

Whewell was also the first to coin the word “Scientist” for that profession which he and his predecessors had been working at for many centuries already. In Newton’s day, as per the title of his most famous

\textsuperscript{18} The Harvest of a Quiet Eye : A Selection of Scientific Quotations (1977), p. 56
\textsuperscript{19} James Clerk Maxwell, in Scientific Worthies I. - Faraday, Nature 8 (1873), p. 400
work the *Principia*, the research into the workings of nature was known merely as “Natural Philosophy”. The term “science” had been used occasionally since antiquity, though with a more general sense and without the specific implications that it was now beginning to entail at the hand of the 19th Century physicists (another word coined by Whewell).

Whewell’s opinion of the definition of science was clear, as he outlined in his great work “*The Philosophy of the Inductive Sciences*”, published in 1840, just as Faraday was carrying out the investigations that would eventually form the core of our knowledge of the nature of electricity.

“*Man is the interpreter of nature, science the right interpretation.*”²⁰

Whewell himself was also a strongly religious man, being an ordained Anglican priest, yet he very much followed in the footsteps of Newton in seeing science not as a threat to his beliefs, but rather as a means of getting to know the work of the deity more intimately.

"*We can perceive that events are brought about not by insulated interpositions of Divine power, exerted in each particular case, but by the establishment of general laws. [...] This has been the view of the relation of the Deity to the universe entertained by the most sagacious and comprehensive minds ever since the true object of natural philosophy has been clearly and steadily apprehended.*”²¹

There are parts of the so-called civilised world where, even today, that sentiment would seem scandalously liberal. Yet opposition to such thinking is largely a product of the 20th Century, not of earlier ages. That is not to say that the new-found powers of science did not trouble the public greatly at times. Then, just as now, the concept of human

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²⁰ William Whewell, *Philosophy of the Inductive Sciences* (1840), Aphorism 17
beings wielding the powers hitherto reserved for deities, caused a great deal of consternation in certain circles. When steam trains first arrived on the scene in the first half of the 19th Century, many were terrified about the effects of such dizzying speeds on the human body. Queen Victoria first plucked up the courage to travel on one in 1842, and her husband, Prince Albert of Saxe-Coburg and Gotha, was known to chastise drivers for travelling too rapidly for his nerves.²²

Electricity, however, was another step up the rung towards apotheosis. And it was not long before this remarkable new power began to impact the lives of ‘ordinary people’.

When the wealthy industrialist George Westinghouse (1846 - 1914) first began to propose that electricity should be wired round the United States using the alternating current methodology proposed by the legendary inventor Nikola Tesla (1856 - 1943) amongst others, he was met by strong opposition, at least partly in the form of Thomas Edison (1847 - 1931), who stood to lose out if his rival’s technology was used over his own direct current system. Edison lost this battle, and Westinghouse consequently led the building of the world’s first grand-scale hydroelectric power station at Niagara Falls, kick-starting the age of electricity. Edison would later win a great many more battles and achieve immortality himself, principally for designing a process which could be used to mass-produce electric light bulbs – the first successful such technology, and one that would make him an extraordinarily wealthy man. Edison’s discovery of the technology behind his light bulb, allegedly taking thousands of trials before the correct recipe was discovered, is probably largely apocryphal, but his legendary tenacity and perseverance are nicely echoed by a quote from William Whewell:

“Every failure is a step to success. Every detection of what is false directs us towards what is true: every trial exhausts some tempting form of error. Not only so; but scarcely any attempt is entirely a failure; scarcely any theory, the result

²²W M Acworth, *The Railways of England*, Chapter 1, (1900)
of steady thought, is altogether false; no tempting form of Error is without some latent charm derived from Truth.”

Whewell is pleasingly quotable. Yet his work was not merely constructed for rhetorical effect, but also to explore several important philosophical questions. Whewell highlighted the purpose of science in his works in a way that has changed little in the intervening years. Firstly, the aim of science is to get at the truth, and only the truth. And secondly, that a scientific theory is worthless if it cannot make new predictions about the Universe that we could go out and test. In Whewell’s own words:

“In art, truth is a means to an end; in science, it is the only end.”

And also

“It is a test of true theories not only to account for but to predict phenomena.”

Until the time of Newton, this latter stipulation had been woefully omitted. Aristotle’s theories sort-of explained what we saw in nature, but they were lousy at making predictions, because they contained far too many free parameters. After all, one could imagine an Aristotelian investigating whether or not certain objects float in water. An apple, so they argue, floats because it is largely water. But yet other fruit do not float, such as some types of grape. Maybe they have slightly less water, and more earth in them? But then limes sink, and lemons float. Why are they different?

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23 William Whewell, No. 7 of his Lectures on the History of Moral Philosophy in England (1852)
24 William Whewell, Philosophy of the Inductive Sciences (1840), Aphorism 25
25 William Whewell, Philosophy of the Inductive Sciences (1840), Aphorism 39
The problem with Aristotelian physics is that it generally provides *post-hoc* explanations. That is to say, it gives a *rationalisation* for why a thing behaves as it does, but it never predicts ahead of time what a truly novel observation might discover. Because of that, and its ability to adapt explanations to fit any observation, the Aristotelian scheme would not today be regarded as a valid scientific theory. The definition of a scientific theory has been formalised throughout the twentieth century, but science broadly requires that a true theory adheres to a number of crucial properties:

1) Scientific theories are, in general, inductive. That is to say, they are the result of *empirical investigation*\(^{26}\), not pure analytical thought.

2) A scientific theory should be in agreement with the existing observations. In fact, it should also be supported by a substantial amount of experimental evidence. It is this high level of evidential support that distinguishes a scientific theory from a mere hypothesis.

3) A scientific theory should make predictions for effects that have not yet been observed but which could, in principle, be investigated. If those predictions are tested and fail to correspond with reality, then the theory should be provisionally rejected in its present form.

The view of Whewell, as well as of Faraday and no doubt all those other prominent figures from the story told in this chapter, was that science was the *only* correct method for interpreting nature, and that it should be shared as widely as possible not just with other like-minded experts, but also with the public at large. In fact, Faraday himself started the tradition of the now-famous Royal Institution Christmas Lectures, giving the 3\(^{rd}\) such lecture himself in 1827 and presenting nineteen instalments of the series in total, with his last in 1860. These celebrated lectures continue today, encouraging experts in diverse fields of science to share their accumulated knowledge with interested young.

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\(^{26}\) In other words, gathering of physical evidence.
school students. And the clear theme of these lectures is not just to extol the valuable discoveries that science has produced, but to share the sense of wonder which drives the desire to explore, to discover, and to learn.

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Looking back at the savagery of the Aztecs we see only one of the echoes of countless civilisations throughout the long and bloody history of humanity who have sought refuge in superstition instead of rational enquiry. The story with which we have occupied ourselves in this chapter has, at its heart, a simple moral: that endeavouring to understand nature provides us with countless transformational benefits than we would never have enjoyed had we made that decision to continue living in deliberate ignorance and fear.

In fact, the story of electricity is a fine example of one arena in which we have not only managed to understand a process once thought to be the realm of the gods alone, but more than that – we have harnessed it for our own uses. Just as Newton helped to dismantle the ages-old picture of the cosmos as being composed of concentric spheres of fixed stars circling the stationary Earth, so too did the study of electromagnetism pull back yet another heavenly curtain, and discover that there really wasn’t anything miraculous to be found there either.

The story of electricity shows us that it is hugely more valuable to know the truth than persist in delusion. For almost all of human history, human beings lived in fear of electricity – terrified of lightning bolts streaking through the skies, crackling with the petulant wrath of violent, unseen deities. Those same human beings, cowering from the celestial onslaught, could not even remotely have dreamed that this same awe-inspiring power would one day be harnessed to power the myriad devices that build up the modern world. They never knew that it would lead to new communication technologies that connected the entire planet; new modes of transportation that could move us around our vast
cities without horse or carriage; light and warmth that keep us safe and comfortable at night.

It is often asked of modern science what the point of theoretical investigation might be. Why, demand the angered citizens, should we fund discovery of the Higgs Boson, or examination of the surface of Mars? What does it benefit humankind to build particle accelerators, to study string theory or to peer deep into the cosmos? My answer to that would be simple: What was the use of William Gilbert studying the peculiar properties of agitated blocks of fossilised tree sap? What possible benefit could such an obscure study ever have hoped to bring? Well, as it happens, although most people today don’t rely on the electrostatic properties of amber in their daily lives, I bet you do use electricity.

The only minor blemish in the story of the discovery of electricity was that this new understanding took a long time before it bore fruit that would positively impact the lives of ordinary men and women. Yet the same was not true for all scientific discoveries taking place at the same time. The nineteenth century was a time of extraordinary change in all aspects of learning, and our story must now make an unexpected change of direction. The next revolution to feature in our journey came not from physics, but from a completely different field of study. It concerns a discovery so instantly shocking and transformational to the human species that, if Newton had lived to learn of it, would have devastated him to the very core of his being.
Ancestry of Life

“If I have ever made any valuable discoveries, it has been due more to patient attention, than to any other talent.”

Newton

I often wonder what it would be like not just to meet the greatest men and women of history, but to arrange for them to meet each other. The geniuses of the history of science often worked alone, sometimes because they were the only ones who actually had any interest in the subjects they were studying, sometimes because they were the only ones with enough money to afford the time to study, and sometimes because they were just plain antisocial. In fact, it seems to be a remarkably common personality trait possessed by pretty much all of history’s greatest achievers, to have a single-minded dedication to one chosen area of study that prevented them from forming the same kind of friendships that others might have enjoyed. This was especially true of Isaac Newton, as we’ve already seen, but it wasn’t necessarily true of all the scientists that we will meet on our journey to the present day.

Although he was also a man of great insight and scientific brilliance, Charles Robert Darwin (1809 - 1882) was, in many other ways, as different to Isaac Newton as it is physically possible to be. Darwin was calm, timid and modest; a polite, happily married man, with a large family and a distinct lack of Newton’s characteristic arrogance; a man plagued with self-doubt, and recurring physical infirmity, greatly admired but also well-liked and respected as a human being as well as a brilliant polymath.
Having said all that, it is certainly true that, as scientists, Darwin and Newton shared much common ground. They were both rigorous experimentalists, for example. In Darwin’s case, that meant spending many years studying the natural world in unprecedented detail and meticulously recording his painstaking investigations so that others could benefit from them. For Newton it meant carrying out a wide range of experiments in order to study the nature of light, refracting sunlight through prisms in his darkened Cambridge rooms and examining the colourful spectra produced.

Newton and Darwin both started their adult lives as profoundly religious men. Newton’s faith, though it departed strongly from the mainline Christianity practiced in 17th Century England, was still one of the strongest influences on his studies right up to his death. Darwin, who also studied at Cambridge, had trained for ordination as a vicar in the Church of England, though by the time of his death had entirely abandoned organised religion, and was as close to atheism as it was politically prudent to admit to being in nineteenth century society. Today, strangely, they are both buried within a stone’s throw of each other in Westminster Abbey, London – one of the most important religious centres in the entire Anglican faith. The irony would, no doubt, not be lost on either of them.

Charles Darwin was very much interested in ‘getting his hands dirty’, in a way that his folk legacy might not fully support. Though he is known today purely for his work on laying the foundation of the theory of Evolution, he was revered in his time as a renowned world expert on molluscs (snails and their ilk), as well as a prominent geologist. Darwin was meticulous and thorough, though also possessed a surprisingly vivid sense of adventure and excitement. The extraordinary diaries he published as The Voyage of the Beagle detail his five year-long journey round the world as a ship’s naturalist, documenting the natural wonders that he saw on his way, dodging bandits and feudal, bloodthirsty natives in Argentina and Tierra del Fuego, surviving a devastating earthquake in Chile, crossing the entire Pacific ocean, and exploring the brand new
colonies of Australia and New Zealand (about which he was not particularly complimentary).

Yet Darwin was also an acknowledged expert in lots of subjects that we would nowadays consider interminably dull. For example, when outlining his theory of evolution he spends many pages discussing the breeding of pigeons – a subject about which he was extremely knowledgeable. He spent many years learning exactly which traits seem to pass from adults to their offspring, investigating the process of heritability (if not the underlying mechanism for it), and understanding that an attentive human breeder could, given sufficient time, breed pigeons with pretty much whatever physical or temperamental characteristics he or she desired. But someone had to be an expert in these things, and without his understanding of pigeon breeding, it is unlikely that Darwin would have formed so cohesive and coherent a theory of Evolution applied to all species, at least on his first try.

It goes without saying that, when discussing the most important scientific theories that have occurred since the time of Newton, Darwin’s theory of Evolution by Natural Selection is perhaps the greatest and most profound – certainly in terms of the impact it had on the human psyche. It is also a perfect example of a theory which has not directly produced any gadgets or devices that we can touch or hold to remind us of the intellectual distance we have travelled – on the contrary, the effects of Darwin’s theory on humanity have been almost purely intellectual, though by spawning the study of genetics and human origins it does offer exciting implications for medicine. Discovering the truth about the tree of life has provided one of the most profound paradigm shifts in the history of our own self-perception.

In fact, this profound discovery was first written down almost simultaneously by both Darwin and also another British naturalist Alfred Russell Wallace (1823 – 1913). Darwin’s extensive and brilliant masterwork, On the Origin of Species was published in 1859, together with Wallace’s findings, causing perhaps less uproar than the popular
accounts of today might imply. Of course, many derided these claims, though the majority of scientists seemed to have accepted the findings and continued about their business almost as if nothing had been discovered of interest whatsoever.

Though Darwin and Wallace differed on many details, it is comforting to know that such great minds had arrived at the same revolutionary conclusions at exactly the same stage in history. Those same conclusions have since been reinforced by a mountain of new evidence unavailable to Victorian science, and evolutionary theory now forms the very basis of all modern biology. Nowadays, to attempt to understand the natural world as we know it without evolution is not merely absurd, but simply impossible.

Darwin’s methods were rather more laboured and painstaking than those of Wallace, who was more of a maverick in his approach. Wallace saw Darwin as a revered senior figure, and sent him some of his early ideas on the subject in 1858 as Darwin was still dithering about whether or not to publish On the Origin of Species. Wallace felt sure that Darwin would find his research interesting, though he probably underestimated just quite how ground-breaking it would turn out to be. It was eventually presented alongside Darwin’s work in 1958, without Wallace’s permission (understandable given that Wallace was completely out of contact in the Malay Archipelago at the time). It was, of course, given full attribution, and Darwin probably expected to share the stage equally, though being the more senior figure and actually being present in London at the time, he ended up taking a substantial majority of the praise as well as the condemnation that it eventually attracted.

We could perhaps compare and contrast the behaviour of Darwin upon receipt of Wallace’s letters from South-East Asia, with the intense clan warfare that surrounded the nearly simultaneous discovery of the calculus of variations by Isaac Newton and Gottfried Leibnitz (1646 – 1716) in the late 17th Century. This famous rivalry hurled the two
scientific entourages into an intellectual mêlée that resulted in a number of high-profile casualties, at least in the scientific sense. Science, it has been repeatedly pointed out, is not a purely cerebral discipline where evidence is calmly gathered and analysed by perfect statisticians, analysed by flawless mathematicians and emotionlessly assimilated by the scientific community – on the contrary, the progress of science often proceeds only by clambering over the intellectual corpses of the generation before. The legendary German physicist Max Planck (1858 – 1947) once said that

“A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.”

Planck perhaps goes too far – one only needs to look at the rapidity with which science is progressing in the 21st Century to realise that it is no longer waiting for the older generation to die before stepping forwards. But that doesn’t mean that there aren’t a great number of bitter feuds within the dusty halls of academic research even today.

Newton’s open conflict with Leibnitz was one of the greatest in scientific history, and it consumed not just the two men themselves, but also most of their extended circle of followers and colleagues. The point of dispute was similar to that of Darwin and Wallace – Newton and Leibnitz had both invented the mathematical process of calculus (or at least, a primitive version of it) at roughly the same time. Hitherto unknown private papers of Newton’s show that he came across the idea in 1666, more than eight years earlier than his competitor, but never got round to formally publishing it. Leibnitz published the idea in 1684, claimed the discovery as his own, and eventually incurred the wrath of Newton and the Royal Society who, while perhaps not being Newton’s greatest friends, at least admired the great man’s intellect, and didn’t want to get beaten to the discovery by a foreigner!
Newton pulled out all stops to prove his priority in the debate, including setting up a committee at the Royal Society to investigate the affair, which was stocked with his own colleagues, never at any point attempted to find his opponent’s side of the story, and resulted in a final report that Newton himself authored. The decision was, of course, biased to the point of complete irrelevance and served as nothing more than a ritual re-assertion of Newton’s own personal dominance of the British scientific community.

Darwin’s experience couldn’t have been more different from this vicious rivalry. Though Wallace was a more junior researcher without Darwin’s reputation, and though the younger scientist had sent Darwin his theory in private from the other side of the world, Darwin ensured that both theories were presented together at the Linnean society, and never attempted to claim primacy or dominance. One imagines that, in the same situation, Newton would have burned Wallace’s manuscript, published his own, and then feigned ignorance. Perhaps I malign him, though I doubt it.

Just as in the case of the Newton/Leibnitz debate, Darwin and Wallace didn’t see eye to eye on every aspect of the theory of evolution. Wallace was unwilling to go quite as far as Darwin did in the assertion that humans originated by the same process, for example, being sceptical that the human brain could have evolved its intricate analytical and social abilities without a little helping hand. Darwin also saw much more of a role of the individual in the process, and especially in sexual selection, where Wallace’s theory dealt with environmental pressures on a larger scale. It’s slightly unfair, but not totally inaccurate to say that in most aspects where they differed, Darwin was later shown to have been right. So perhaps Darwin deserves to be remembered more prominently than Wallace. As for Newton and Leibnitz, well it is universally agreed now that Newton was the first to discover calculus, though the notation we use in modern mathematics is almost entirely taken from that invented by Leibnitz, whose own method was much less complicated. So things worked out fairly in the end.
Darwin’s inspiration didn’t just come from his own research and that of his colleague Wallace. In fact, his paternal grandfather, Erasmus Darwin (1731 – 1802), had already written about the process of evolution before his illustrious grandson was even born. Erasmus Darwin was a doctor and a philanthropist, with a mind that would probably have felt more at home in today’s enlightened world than at the beginning of the nineteenth century. In his book *Zoonomia*, he had written not only about the theory of common descent, suggesting that every living thing on Earth shares a distant common ancestor, but also about how this remarkable family tree had led to the world of diversity that we see today. Erasmus was also a keen advocate for gender equality in a world where women were still very much regarded as second class citizens. Charles’s pedigree was very much of good, kind, hard-working, socially-progressive folk, though forcefully intelligent with it.

Charles definitely knew what his illustrious grandfather had written, though we may never know whether he allowed this to guide his thought process as he examined the hundred or so new species unique to the Galapagos Islands, on his famous five-year circumnavigatory voyage aboard H.M.S Beagle. His own personal journals show that he approached the question very much with an open mind and, in fact, even after the return from Galapagos, his diaries show that he was still largely convinced by the doctrine of divine creation with which he had been raised as a child.

It is tempting to see the Theory of Evolution as one spark of genius that suddenly struck the young Darwin aboard the Beagle, a story popularised over the last century or so. However, this seems not to fit with the evidence. Darwin’s own personal struggle with Evolution lasted a full twenty years, with his ideas gradually coalescing into a theory that he knew to be dangerous, but which he could no longer deny. Even given his own conviction and extensive studies in the subject, it was an incredibly brave decision to publish that theory, and an even braver decision to do so at the Linnean Society in London, one
of the foremost centres of scientific excellence worldwide. Some colleagues loved it instantly. Others despised it, and went to their graves trying unsuccessfully to prove it wrong. The division seemed unrelated to intellect or experience, but rather to what Albert Einstein would later term the “hereditary prejudices”\(^27\) that so divisively plague much of human thought.

Today Darwinian theory forms the bedrock to our view of life on Earth. No other scientific idea since Copernicus has changed our view of the Universe around us so completely in such a short period of time. It answers so many fundamental questions about life, but it poses many more, some of which are only now being answered with 21\(^{st}\) century investigation. Most importantly though, it offers an explanation for the great diversity of life from microscopic bacteria right up to mice, dogs, gorillas and humankind. This was an explanation that tied all these disparate parts together under one unifying umbrella – beautifully simple yet inconceivably powerful.

Don’t believe anyone who claims that we now understand every single aspect of evolution – there are still a few corners that need straightening out. Having said that, the theory itself has been in no doubt whatsoever for well over a century. Evolution, when taken literally, means just one thing: “change”. Of course, that change can happen in many different ways. Darwin suggested one method, which was ‘natural selection’. Many others have competed with it since though this, with very few alterations, remains at the heart of the modern theory. Though this was a revolutionary breakthrough, it was actually the theory of common descent, claiming that all life on Earth has descended from a single primitive ancestor, that most incensed Darwin’s contemporaries.

Darwin was rather less well prepared to debate those same adversaries than Newton was. He was not an extroverted man, preferring solitude and the quiet, unstressed country life. Stress and confrontation made him violently ill, and he often refused visitors at home for fear of

\(^{27}\) Albert Einstein, quoted in the *New York Times*, March 19, 1940
embarrassing himself with his sickness. Instead, the role of public
defender of Darwin’s theory was taken by the biologist Thomas Henry
Huxley (1825 – 1895). So fiercely did he defend his friend’s work that he
became known as “Darwin’s Bulldog”. Starting in 1859, and continuing
throughout the early 1860s, Huxley took on all critics of Darwin’s
theory, both in print and in person, including one infamous debate
where battled Bishop Wilberforce of Oxford at a meeting of the British
Association for the Advancement of Science. The debate was messy,
and there was no clear winner at the time, despite Huxley landing some
powerful rhetorical blows. But it proved something of a turning point
for Darwin’s theory, and within a few decades the majority opinion of
the scientific establishment was that the Theory of Evolution was
broadly correct. Darwin himself seemed puzzled by the religious
opposition to his theory, writing in his notebooks

“We can allow satellites, planets, suns, universe, nay whole
systems of universe, to be governed by laws, but the smallest
insect, we wish to be created at once by special act.”

Some humans are often keen to describe our species as ‘better’ than all
other forms of life because we’ve discovered nuclear weapons and
satellite television. Others might argue that we are worse for exactly
the same reasons. Either way, there is not a human alive who can run
as fast as a cheetah, who can lift as much as an elephant, who can swim
as fast as a dolphin, who can fly (at all), who can see as well as an
eagle, who has a sense of smell as keen as a dog’s. We’ve not
discovered biological echolocation, we can’t breathe underwater, most
of us can’t even lift our own body weight, we can’t burrow, we can’t
survive in extremes of cold or heat, we can’t moult, we can’t kill
buffalo with our teeth, we can’t navigate by polarised light, we can’t see
in the dark, we can’t survive without water for weeks, we can’t
adaptively camouflage ourselves, we have neither armoured scales nor
spines, we don’t generate our own poison, we can’t hibernate and we’re
born into this world about the most pathetic, helpless babies of all the

28 Charles Darwin, *Notebook N* (1838)
mammals. If there were an all-animal knockout fighting competition, we’d come second-last in the human-weight division, beating only the sloth. We can even be killed by entities as tiny as bacteria or viruses. Yet we still insist on declaring ourselves the ‘greatest’ species on Earth?

Human beings have their strengths and weaknesses. Sure, we can’t do many of the things above, but we can do many more things that no animal has ever done. Like read this book. But let’s abandon for now this absurd human notion of how we’re ‘better’ than everything else. Let’s just look at all of life as one broad tapestry, within which we have carved ourselves a fairly substantial niche. There is a wide spectrum in this game of survival. We simply inhabit one end of it, together with the larger mammals. This is one ‘solution’ to life – enormously powerful individuals but few in number. Animals such as humans and other primates each have a huge impact on their environment, though they are themselves (relatively) rare. Lower down the spectrum we find rodents and then insects. As we follow in this direction, we find much simpler animals in increasing number. Ants are no ‘better’ or ‘worse’ than humans – they exist successfully, and so do we. There are something like 7 billion human beings on this planet. But for each human being, there are an estimated 200 million insects.29

Further down the scale of life we get to microscopic organisms such as bacteria, followed by viruses. These exist in vastly increasing number, but vastly decreasing size and complexity. Once we reach viruses, we’re really at the edge of what could be considered ‘alive’, though it turns out that this is a very complex line to determine.

So how does this all relate to the principle of natural selection? Well this is the key to the whole theory – this is why natural selection is so vitally important. Natural selection allowed biological organisms to develop from a sea of randomly interacting chemicals. Without this

potent driving force, the world would still be inhabited by a drab selection of molecules, destroying and rebuilding each other day after day for eternity, entirely by chance. Natural selection makes it possible for complexity to arise. And that’s where it begins to get interesting.

We know that there was nothing on earth but lifeless chemicals for approximately one billion years after the planet’s formation. Then, within the space of the next few billion years, these chemicals began arranging themselves into rather more sociable forms. About one billion years ago, organisms certainly recognisable as living creatures were swimming about in inhospitable seas. Over the next 500 million years or so (and we still don’t know the exact order in which this happened), life began to diversify into more advanced forms.

About 540 million years ago, at the beginning of a period known as the ‘Cambrian’, the fossil record shows something remarkable: Up to this point there are hardly any fossilised creatures surviving, then over a (geologically) short period we find a huge multitude of these fantastic, elaborate forms. The effect is so dramatic that it has been called the ‘Cambrian Explosion’.

The Cambrian Explosion could easily be seen as the dawn of complex life. It is not clear whether the number of creatures actually increased at this point or, more likely, that the existing species of living creatures became sturdier, and hence more readily fossilised. This could be due to the evolution of harder and more durable body parts, or just because of the changing environment in which these creatures lived.

Whatever happened up to this point (and many good books have been written on just this one early period), complex life as we know it began in the early Cambrian. Then, for the last 12% of the earth’s history, these simple, invertebrate organisms developed through fish, crustaceans, reptiles, animals and plants, dinosaurs, birds, mammals and human beings. It was as if everything in existence had been scrambling
around fruitlessly at the bottom of a deep chasm, and then suddenly somebody invented ladders.

In fact, Evolution by Natural Selection is the ladder of life. It is the only process that allows magnificent creatures like us to develop from the simplest of building blocks. It is not a magical fluke or blind chance – it’s an unavoidable consequence of several obvious truths. In Darwin’s time there were excuses for doubting his theory; nobody knew about genetics, for a start. However, it was impossible to argue with the principle of selection. That bit was, of course, obvious. If somebody doubts that natural selection is a viable process then they clearly haven’t understood it. The controversy of Darwin’s work was that he applied this process to explain the origin and diversity of life and, in particular, human beings.

The process of evolution through ‘the survival of the fittest’ is actually remarkably simple, and it goes something like this:

A population of individuals exists in some environment. These individuals are not identical, but vary slightly from each other. They are free to interact both with their environment and with their neighbours. They require certain resources in order to survive, but these resources are limited. Each individual’s behaviour is modified by the unique properties of that individual, which are inherited, at least partially, through a reproductive process. An individual’s survival and reproductive success may be largely random, though they are also biased by each individual’s ability to make effective use of its environment.

Maybe that sounds a bit like it’s been written by a lawyer, and perhaps that’s my fault, though I did write that paragraph carefully to illustrate one important point: If you read it through again, then you will notice that I never at any time mentioned anything about living creatures. The concept of ‘reproduction’ is just as applicable to viruses or computer
code as it is to leopards or gazelles. Reproduction simply means ‘copying’. Likewise for the concepts of ‘resources’ and ‘behaviour’. A computer program uses resources (memory, storage space, processor cycles) and produces behaviour (output). Its behaviour is dictated by the way it was programmed. In most living creatures this code is represented using a sequence of chemicals. In a computer program, it could be a series of instructions or numbers. Researchers can imitate evolution by natural selection in a computer and use that exact same process to discover powerful new results – often better than any human would have found on their own.

So evolution by natural selection, as I described it above, isn’t uniquely relevant to living creatures, but let’s consider what would happen if we applied this process to the living world. You need to accept six simple facts, and from this the entire theory becomes undeniable.

1. Living things can create more than one offspring per parent.
2. The Earth is very much older than any creature within it.
3. The Earth’s resources are limited.
4. Individual creatures vary from one another.
5. A creature’s physical attributes will affect its survival and reproductive success.
6. At least some of these variations can be partially passed on from parent to child through reproduction.

If you accept all six of these facts then you cannot doubt evolution. Let me explain.

Firstly (using facts 1,2), you can see that there has been enough time for even the least promiscuous species to completely suffocate the Earth with an uncountable number of offspring. If you start with a single couple and double the population every century, then you could reach the present-day human population of the Earth in only a few thousand years. But we know that humans – and all large animal species – have been around for much longer than that!
Clearly a species can’t just go on breeding unchecked forever because of fact 3 – there just isn’t enough space on the Earth to accommodate everyone. What’s more, there’s not enough food for everyone, either. In fact, it gets worse – all animals, in order to survive, need to eat other living things. This means that some individuals, be they predator or prey, will not survive long enough to reproduce. Populations therefore stabilise at the level that their environment can support. Some animals produce remarkably few offspring (humans being the most obvious example), and some others produce literally millions. In a stable population, the number of surviving offspring is always going to be roughly one per parent, which really means two per female. At this rate, each individual exactly replaces itself in the next generation, keeping the population stable.

If two parents can produce more than two healthy offspring then the population will grow, and if they produce fewer than this then the population will shrink (assuming lifespans stay the same). Thousands of years ago before modern medicine and technology, the average human couple may have had eight or ten children, of which only a few would survive to adulthood. The average female fish may lay thousands of eggs, but we would still expect roughly two of those to survive long enough to repeat the process. Evolution is a numbers game and there are many ways to play.

So, what determines which individuals survive and which do not? Of course there are many unpredictable factors like weather, abundance of food and disease. However, several other traits could give one individual or group of individuals an advantage over others of the same species (facts 4,5). For example, being slightly faster, taller, nimbler, harder to see, stronger, more resilient to cold or heat, more resistant to disease or more fertile. The advantage may be very tiny indeed – that doesn’t matter. All that matters is that there is a slight benefit which, when you add it up over the entire population of individuals and
perhaps over many thousands of generations, translates to a real and measurable advantage.

An inheritable trait that gives an individual one part in a thousand better chance of producing fertile offspring would have very little effect on that same individual, and indeed it would probably not even be measurable. But if you multiply it by millions and pass it down through the genetic code over many generations, it eventually begins to add up. Those individuals that are slightly more likely to breed and produce viable offspring, are slightly better adapted to the challenge of existing – and they pass on their secrets to their children (fact 6). And only theirs.

Imagine a population of fish in a lake, where one female is born with a mutation that allows her to lay slightly more eggs than her peers. This one individual should have slightly more offspring in the next generation compared to the other fish without this mutation. Because this trait is inherited, then those offspring will have more offspring themselves, and so on. Let’s say we start with one fish in every hundred with a mutation allowing her to produce 5% more eggs, and let’s say that it is inherited by all of her children, and all their children, and so on. Barring catastrophes, after just under one hundred years this one individual’s direct descendants now be in the majority. Small changes add up to large effects if you wait for long enough. A century, in evolutionary terms, is a heartbeat.

The most important thing to remember here is that this is not a chance process. Perhaps the most common mistake when learning about evolution is to assume that it’s random. Even extremely bright scientists, who should have known better, have made this mistake. Of course, you can now see that evolution isn’t random at all – it’s an inevitable and unavoidable consequence of the way the natural world works.
Imagine a mountain range during a rainstorm. Where do the raindrops fall? Of course they fall completely randomly across the entire landscape. So let’s fast-forward a few hours. Where is all the water now? Why is it that the rain water always seems to gather in the same rivers, streams and lakes? If you looked at the chance of all the rain falling in exactly those places then you would conclude that the ‘rain theory’ of water was completely false. But of course, we know that this is not a chance process. The rain falls at random in an even pattern across the landscape, but after falling it follows fixed, predictable laws. It gathers in furrows and hollows, flowing along mountain streams into the lakes and rivers because gravity says that it must. That’s just like Evolution.

It’s easy to forget that the process of Evolution is a gradual affair, with individual species changing very slowly over time, and new species diverging from old ones at a barely perceptible rate. Though a gorilla seems very different from an antelope, the similarities are many: Four limbs, herbivorous, two eyes, fur, skin, one heart, one liver, one brain protected by a bony skull, two lungs, a brain, a digestive tract, similar immune systems, similar blood composition and cellular structure, live births etc. Sometimes external appearances can be deceptive.

So evolution by natural selection is a general process that arises unavoidably in real-world populations. It explains how chaotic, disordered conditions can actually give rise to order and adaptation. In evolution, every individual is continually being tested. Only those that are able to get the greatest use out of their environment are given the privilege of creating the next generation. Natural selection shows us how life evolved to such a finely-tuned degree that it gave the illusion of having been designed – an illusion that fooled mankind for millennia. And, in some places, rather embarrassingly, still does.

To put it bluntly, everything living thing you see around you (including yourself) is here simply because its ancestors were good at reproducing themselves. In the words of British evolutionary zoologist Richard
Dawkins, evolution can be succinctly described in one sentence: “The world becomes full of organisms that have what it takes to become ancestors.”

Applying the term ‘ancestors’ is just as valid to bacteria as it is to ants, trees, humans and orang-utans. Or computer code. And your chain of ancestors stretches back a long way further than the mysterious great-great-grandparents you’ve only ever seen in tattered old black & white photographs.

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The contents of this chapter concern fundamental paradigm shifts in how we see ourselves, rather than the Universe outside of ourselves. Astronomy (since Copernicus) was beginning to show us our true place in the cosmos; physics was beginning to explain our place in geological time, especially through estimates it provided for the age of the earth thanks to scientists such as Lord Kelvin (1824 - 1907), and now Darwin was showing us our true place in biology. All were humbling, but though the findings of geology and cosmology offer us cold, hard numbers which bamboozle our minds and provide us with the humbling yet awe-inspiring perspective of the fabric of the Universe, Darwin’s discovery offers us a homely family tale. Darwin brings us together, and turns disparate species and genera into branches of one big family.

Though the fact of Evolution is now a fundamental part of modern biology, accepted by all sensible scientists working in any related field of study, Darwin’s idea has had a hard time obtaining any kind of traction outside of academia, especially in the more religiously conservative societies of the southern United States, and in the Islamic world. Like much of modern science, Evolution is not a theory that can be grasped easily – it requires a certain level of study to understand it, yet it’s very easy to think that one understands it, to mischaracterise it and to build a ridiculous ‘straw man’ against which to argue – a

caricature of the theory that, because of its inaccuracies, is misleadingly easy to argue against.

The story of scientific progress has taught us all that we should strive to develop an awareness of the limitations of our own brains. We try to build up belief systems that, as far as we can tell, best represent the true state of the Universe but sometimes we get things wrong, and our brain is not always very helpful when it comes to identifying the mistakes we’ve made, and working out how to correct them. Our brain works to defend us from emotional distress, often by hiding from our conscious mind those very facts that would overturn our fragile misunderstandings. A now legendary study\(^{31}\) looked at how our perception of our own abilities varies with the actual level of those abilities, and discovered that those who are far below average in some skill or area of knowledge are likely to overestimate their own ability, often quite considerably, relative to those around them. On the other hand, those with high levels of skill often underestimate their level of skill relative to others, because they overestimate the skill levels of their peers. The implication of this study is that those who have not had the good fortune of a broad and unbiased scientific education are more likely not only to misunderstand complex topics such as evolution, but also to be overconfident in their own (flawed) understanding.

Despite the overwhelming expert consensus in favour of the modern study of biology, we probably ought to be more understanding of those who refuse to accept the mechanism of Evolution – after all, it wasn’t until the 1920s when scientists really began to understand the process of Natural Selection, and Darwin himself was unaware of genetics – a science that only really got going in the 1930s. Much could perhaps be made of the fact that Darwin was so convinced by the analytical arguments for Evolution and the experimental evidence of evolutionary processes at work that he didn’t need to understand the underlying

mechanism by which it operated. As I said earlier, this reminds us of Newton, who convinced himself of the truth of his theory of gravity without the slightest idea how an action could take place at a distance such as the vast separation of planets in the solar system - he expected there to be some mind of medium through which it worked, but he never demonstrated that one existed, and didn’t seem to be very bothered by that fact.

A statement that I believe that both Darwin and Newton would have approved of would be this: *Empirical knowledge forms the bedrock of scientific investigation*. You can theorise all you want behind closed doors, but in the cold light of day, an experimental result will either confirm or disconfirm your theory. And when experiment disagrees with theory, experiment wins. Darwin himself viewed the careful and accurate collection of scientific evidence to be paramount to the process of science.

> “False facts are highly injurious to the progress of science, for they often endure long; but false views, if supported by some evidence, do little harm, for every one takes a salutary pleasure in proving their falseness.”32

To paraphrase, if you come up with a false view, even if it is supported by some evidence, then it doesn’t matter too much because sooner or later the evidence will win through. But false facts – lies or biased evidence – are far more dangerous, because they form the foundation for false theories that are far less easily dislodged.

The story of Evolution is simultaneously one of the proudest and one of the most disappointing periods in scientific history. It highlights the emotional way in which scientists often respond to challenges to their preconceived notions, and how often it takes far too long for obvious truths to become accepted by the community as a whole. Yet it also offers a great deal of hope, and I firmly believe that Darwin’s theory

gives us a heart-warming picture of our extended family, bringing us all together in one long, unbroken lineage tracing back billions of years to the most humble of beginnings.

Though if we look carefully at the shadowy extremities of our family tree, we may uncover some far more sinister relatives; isolated from us by deep geological time, but close enough that even in the 21st Century, they pose arguably the greatest single threat to humanity. And it is into their unfamiliar and invisible world that we must, with trepidation, enter next.
The Hidden Assassin

“We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.”

Newton

The Twentieth Century was undoubtedly an era of staggering, nearly apocalyptic bloodshed. Within the space of thirty years came two global wars which devastated vast swathes of the globe and massacred untold millions of human beings; men, women, children of all nations – none was spared the carnage. Throughout recorded history the human race has descended into vicious slaughter on countless occasions, suffering colossal loss of life from seemingly incessant large-scale warfare across all its inhabited lands.

Yet even the ungraspable mountain of corpses generated by the opposing forces in the First World War, one of the bloodiest conflicts in human history, is dwarfed by the staggering death toll from the disease epidemics which followed. The Spanish Influenza outbreak in 1918-20 killed, by some estimates, as many as 50 million people worldwide,\(^{33}\) sparing nobody, taking no prisoners and granting no mercy.

Perhaps the most startling difference between these two brutal scourges of humanity is that, whereas the causes and mechanics of warfare have been well studied since antiquity, the understanding of disease only

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\(^{33}\) Taubenberger, J., & Morens, D., 2006, Centers for Disease Control and Prevention Historical Review
really began to take off in the mid-Nineteenth century, and for the entire history of humanity before that, the greatest cause of death in human civilisation was a complete mystery to everyone. Either it was a curse from some supernatural entity, or the pernicious result of terrifying unseen forces acting against us from the shadows. And there was nothing humankind could do to combat this invisible scourge.

The modern picture of disease, perhaps more than any other subject that I will talk about in this book, illustrates a staggering change in perception that is so complete that few would even be able to contemplate what life might have been like before its secrets were first unravelled. To cast our minds back to the early 1800s is to enter a realm of profound and paralysing ignorance. The threat of disease hung perpetually overhead like Damocles’ sword, poised to slay at any minute without warning. At any time and at any age, one could discover the terrifying first signs of a contagion that would lead to an unstoppable slide into agony, suffering and death, and despite the best efforts of the greatest minds throughout history, this hidden assassin never revealed its macabre secrets. In the face of such an adversary, the scientific community, diverse and unstructured as it was at the time, had no weapons to bear. Humanity was helpless.

The great and terrifying mystery of disease did not stop many people from concocting their own models for what was going on in the bodies of the ill and dying. Though the underlying mechanisms by which the human body works were beyond even the greatest analytical minds of the time, there are always some for whom an abject lack of understanding is no barrier to forming strong opinions. And, of course, without the experimental input that began to appear in the mid-1800s, the best theories were no more than wild guesswork.

Since classical times, it was believed that much of bad health related to the quality of the air that one breathed. And, like many primitive models for disease, this theory had a certain degree of accuracy to it. After all, we now know that smoke and pollution in our air damages our
lungs, that cigarette smoking causes all manner of debilitating respiratory diseases and that odourless airborne toxins such as Carbon Monoxide can be lethal if undetected. But that’s about as far as our modern fight against ‘bad air’ would stretch. Yet Miasma theory, which held that all disease was due to bad air, remained the prevailing theory for much of the medical community right up unto the 1860s,

Though the miasma theory was not correct, it spawned a long line of treatments that, though based on an incorrect understanding of medical science, were actually accidentally beneficial. For example, dirty air does carry dangerous chemical pollutants – especially in the 19th century where the coal-fired smoke stacks of the industrial revolution were belching their filth into and over every household in the major cities of the developed world. So getting patients away from dirty cities and out into the fresh, clear air of the countryside was beneficial for a patient’s health and in many cases this would have resulted in an improvement of their conditions. Perhaps this undeniable, yet accidental, positive side-effect of miasma theory contributed to its longevity – after all, human beings have always had a profound weakness for anecdotal evidence. Yet for a large variety of diseases, even the allure of spas and country exercise were not sufficient to heal the patient of their afflictions. Unknown to the doctors of the time, the foe was not without, but within.

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The first glimpses of the theory of infectious disease – the idea that disease is spread from person to person by means of some kind of particle that could be transferred by touch and close contact – actually began to appear in the mid-sixteenth century, a century before Newton was born and several centuries before medicine really began to uncover the secrets of disease. This first glimpse of a vaguely modern theory appeared in the extraordinarily prescient writings of the Italian polymath Girolamo Fracastoro (1478 – 1553), who published in 1546 his book On Contagion, Contagious Diseases and Their Cure, advancing the idea that disease was, in fact, caused by “spores of contagion”.

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These same spores could be carried just like those of a plant, passed between nearby people or carried on the wind.

Fracastoro was the first to describe typhus, a contagious disease that was a significant cause of death in the middle ages, especially among populations kept in cramped living conditions within jails and army barracks. Typhus kills fairly rapidly, with the victims suffering from an extreme fever, severe psychological distress, painful rashes and excruciating muscle pain. A substantial fraction of those contracting the disease will die, sometimes as many as 60%, and the infection is especially fatal amongst the old and infirm.

It is a sobering thought that throughout the middle ages, especially in the 16th and 17th centuries, the largest proportion of casualties from most wars were typhus victims, and only a minority were actually killed in combat. Physician Hans Zinsser states that the Thirty years war (1618-1648) between the Catholic and Protestant European powers was “the most gigantic natural experiment in epidemiology to which mankind has ever been subjected”34. Thousands of soldiers and peasants on each side during the Swedish siege of Nuremberg in 1632 died from epidemic typhus running rampant through the cramped army barracks, and the disease contributed significantly to a catastrophic destruction of the German population that took well over a century to recover.

In fact, the history of typhus goes back a long time. The Greek historian Thucydides describes a plague that contributed heavily to the downfall of Athens in its war against Sparta in 430 BC. The symptoms sound extremely typhus-like.

\[ \text{People in good health were all of a sudden attacked by violent heats in the head, and redness and inflammation in the eyes, the inward parts, such as the throat or tongue,} \]

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34 Zinsser’s work on the death toll of typhus throughout the ages, “Rats, Lice and History”, was republished in 2007.
Entomologist and historian Joseph M. Conlon describes some of the historical effects of typhus, including destroying the army of Ferdinand and Isabella in their attempts to banish the Moors from Spain (1489, 17,000 deaths). Later the disease interceded in the wars between Charles V of Spain and Francis I of France (25,000 French soldiers died, Charles V was delivered from almost certain defeat and was instead crowned Holy Roman Emperor in 1530). Charles V was himself later thwarted by the same disease, losing 10,000 of his soldiers during a subsequently aborted attempt to gain control over modern-day Germany.

The grim tale continues in a similar vein. Ten million died of typhus during the 30 Years War (1618-1648), which exceeded the number of military deaths thirty-fold. Later wars were influenced by typhus, too. It is uncertain the extent to which it influenced Napoleon’s defeat in Russia in 1812, though it is known that his armies suffered perhaps as many as half a million casualties to the disease. Of the 600,000 soldiers who left France in 1812, only 3,000 were still alive by June 1813. This first disaster was followed up by a second campaign involving another 500,000 men (who apparently hadn’t read about the previous year’s catastrophe), 219,000 of whom would die of typhus before Christmas. It is no exaggeration to say that typhus, more than military loss or strategic error, led to the eventual defeat of Napoleon in 1815.

The 19th Century saw no reduction in the terror of typhus. During the Irish Potato Famine of 1846 roughly 190,000 met their end due to the disease, and the toll was also high in the Crimean war of 1853-6, where nearly a million soldiers were removed from combat due to typhus,

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35 History of the Peloponnesian War, Thucydides, c. 311 BC
36 Many of the subsequent statistics come from The Historical Impact of Epidemic Typhus, Joseph M Conlon, University of Montana
cholera and dysentery. Roughly 100,000 men eventually died from those illnesses combined.

Yet despite the staggering death toll exacted by this terrifying disease, it wasn’t until the 20th century that the primary vector for transmission of typhus was identified. Far from being carried in “bad air”, typhus was transmitted by the lowly louse. This discovery was made through the pioneering work of French bacteriologist Charles Nicolle (1866 – 1936) in 1909, or which he received the Nobel Prize for medicine in 1928. With this new-found knowledge, typhus could now be combatted through cleanliness, yet knowledge alone does not eradicate disease. A decade later, in the Russian civil war of 1917-1922, estimates suggest that up to 3 million, largely civilians, perished from the disease.\(^{37}\)

Concentrated de-lousing efforts in military hospitals and jails helped to stem the tide of the infection, but it wasn’t until the first use of the insecticide DDT in 1939 that the battle really turned in favour of humanity once more. Having said that, without tight controls the disease could still get a foothold. Typhus outbreaks in Germany during the Second World War likely caused thousands of deaths. Even today tens of thousands of people still die of this disease worldwide every year, largely in sub-Saharan Africa\(^{38}\). Typhus kills over a third of the people who contract it, even though it can easily be prevented through cleanliness or cured with a simple and cheap course of antibiotics.

So that’s typhus, a single disease that has had a larger impact on human history, and certainly a larger death-toll, than the most vicious and evil of dictators. Yet though this gruesome disease was first discussed by Fracasstoro in the 16th century, it wasn’t until 400 years later than anyone worked out what caused it. In those intervening years, it had killed (conservatively) tens of millions of people worldwide. Nowadays, in the Western world at least, the death toll is effectively zero and you almost certainly never came into contact with it, nor

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\(^{38}\) WHO Statistical Information System (WHOSIS)
worried about contracting it at any point in your life. Because of

Typhus is just one example, but I could give many more. The obvious, and perhaps more famous, example is the bubonic plague – a disease carried by fleas on rats that was responsible for the deaths of staggering numbers of people worldwide – almost certainly more than typhus, though the numbers are very difficult to compile. In one major outbreak in the 14th Century, now known as the “Black Death”, it killed possibly as many as 50 million people in Europe alone\(^39\) – well over half the population of the entire continent at the time. The death toll worldwide could have been twice this number.

Faced with a terror of this magnitude, you can be certain that the general public and the intelligentsia alike were clamouring for explanations, and many panels of experts were dispatched to examine this deadly malady before it wiped out entire nations. In 1348, the esteemed Paris Medical Faculty wrote an account of the disease under the orders of Philip VI of Valois, King of France\(^40\). The account runs to three chapters, explaining in great depth the observations made by these learned doctors, having sought the accumulated wisdom of all Europe. They concluded that the plague arose “from a double cause,” explaining that

> “One cause is distant and from above, and pertains to the heavens; the other is near and from below and pertains to the earth, and is dependent, causally and effectively, on the first cause.”

All of which sounds fantastic enough, but what were those two causes?

\(^39\) Ole J. Benedictow, *History Today* Volume: 55 Issue: 3 2005

\(^40\) Subsequent quotes taken from a translation of this account by Rosemary Horrox, as quoted, together with other contemporary reactions, in “The Black Death” (1994) [http://www.stanford.edu/class/history13/Readings/Horrox.htm]

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“We say that the distant and first cause of this pestilence was and is the configuration of the heavens. In 1345, at one hour after noon on 20 March, there was a major conjunction of three planets in Aquarius. This conjunction, along with other earlier conjunctions and eclipses, by causing a deadly corruption of the air around us, signifies mortality and famine ... the conjunction of Mars and Jupiter causes a great pestilence in the air, especially when they come together in a hot, wet sign, as was the case in 1345. For Jupiter, being wet and hot, draws up evil vapours from the earth and Mars, because it is immoderately hot and dry, then ignites the vapours, and as a result there were lightning, sparks, noxious vapours and fires throughout the air.”

I think the most interesting aspect of this passage is not the explanation they give – in all fairness, they didn’t have the knowledge or technology to determine the actual cause of the disease in the 14th Century. What’s actually interesting is the style with which they write. This is not the sort of writing that we would nowadays associate with science. Scientific writing is cautious, statistical, nervous, thorough, detailed, passive and incredibly dry. What we have here is primitive superstitious speculation reported with a ludicrous and undeserved level of confidence. And what’s most surprising about the report is the complete lack of evidence provided.

Some claims such as “Jupiter is wet and hot” seem extraordinary. How do they know this? What measurements could they possibly have taken to verify this? We now know that Jupiter has only trace amounts of water vapour in its atmosphere – it is composed mainly of Hydrogen, with some Helium. In fact, water makes up approximately four parts per million of the atmosphere, and we know that fact thanks to modern studies using the technique of spectroscopy, as well as from the Galileo probe that we actually dropped directly into the Jovian atmosphere in December 1995.
And Jupiter most certainly is not hot. Being roughly five times further away from the Sun than the Earth is, Jupiter receives 25 times less solar energy for each square metre of its surface, and as a result, it gets really cold. Of course, it’s difficult to define the surface of a body made almost entirely of gas at varying pressures, but if we measure the temperature where the atmospheric pressure is the same as that of the Earth, then Jupiter is more than 100 degrees Celsius below zero – far colder than the coldest natural temperature ever recorded on Earth. Again, the Galileo probe told us that, but we could also tell by observing the light that Jupiter gives off, and examining how it compares with computational models. As for Mars, well it may be fairly dry, but it certainly is not hot, with an average surface temperature of around 55 degrees Celsius below zero.

Modern science gives us techniques for roaming through space and discovering the true nature of the planets in our Solar System. Real scientific explanations are full of details, backed by evidence and rational argumentation. Science doesn’t rely on intuition, instinct or guesswork. Yet the report of 1348 reads very differently – confident, yet without any justification whatsoever.

So what was the second cause of the Black Death, according to the French Doctors’ Report? Well, they blame “bad air”. Not entirely unreasonable, one might argue. Though they do claim that a major cause of that toxic situation might have been “the escape of the rottenness trapped in the centre of the earth as a result of earthquakes” which had, apparently, recently occurred in France. This image, to me at least, conjures up Dantesque images of hell releasing its noxious fumes through momentary fissures in the Earth’s crust. So again, more wishful thinking than anything but at least less implausible than the first explanation. But again, though the second explanation started off reasonably well, it soon becomes apparent what the origin of this “bad air” must be:
“Air, being pure and clear by nature, can only become putrid or corrupt by being mixed with something else, that is to say, with evil vapours. What happened was that the many vapours which had been corrupted at the time of the conjunction were drawn up from the earth and water, and were then mixed with the air and spread abroad by frequent gusts of wind...”

So we’re back at astrology and guesswork. The report also goes on to implicate the weather (fair enough), comets and meteor storms (less so) and those who follow a bad lifestyle “with too much exercise, sex and bathing”. The mind boggles. One can but wonder how much damage wild and uninformed speculation like this might have caused amongst the ignorant minds to which it was disseminated. The advice to avoid exercise and bathing is pretty much the opposite of what any competent doctor would advise now in order to fight off infection, and this seems more to represent the prejudices of the authors than to qualify as a verifiable, tested conclusion.

The fact that the greatest scholars in 14th Century France wrote a totally serious report to the King of that rich and powerful nation explaining that the most deadly pestilence in human civilisation came about because “Mars was … looking upon Jupiter with a hostile aspect” should give us pause for thought. And, moreover, it should give us great occasion for gratitude for how far the scientific endeavour has come in those six and a half centuries.

We ought also to take note of the esteemed sources quoted by the authors of that academic paper – Aristotle, Hippocrates and Ptolemy. Medicine had made literally no advances whatsoever in well over a thousand years – nearly 1700 years perhaps if we go back to Aristotle, whom they quote the most frequently. Indeed, the lack of progress is truly staggering. Yet from what we know already of the early days of Newton in Cambridge, even after the Black Death, the next 300 years would deliver very little more. All of this makes the scientific progress
of the 18\textsuperscript{th} and 19\textsuperscript{th} centuries seem far more remarkable by their extraordinary rapidity.

Even though medical science has progressed to an almost miraculous degree since the time of the Black Death, we shouldn’t assume that medical fiction has completely gone away – the human body is extremely complicated, and it’s still embarrassingly easy for a cunning fraudster to invent plausible-sounding nonsense and con the gullible out of their money, their health, and sometimes their lives.

Of course Isaac Newton was not immune to the threat of disease, though he seems to have escaped for most of his life without any major illnesses to speak of. In fact, his death at the age of 84 was remarkably ancient for the 18\textsuperscript{th} Century. As I mentioned earlier, he had a narrow escape from the plague himself, when it swept through London in 1665-1666. It was during this period that Cambridge University was temporarily disbanded, and Newton returned home to Woolsthorpe, where we find the origin of the (probably apocryphal) story of Newton watching an apple fall, which triggered his thoughts about gravitation. The apple story may well be fiction, but it is certainly true that his first thought on gravity began in this period, as well as his first use of his method of \textit{fluxions}, which would later be developed into the calculus that we met in the last chapter.

The 17\textsuperscript{th} Century plague in London was a severe epidemic, though perhaps not quite as vicious as the 14\textsuperscript{th} Century Black Death. Estimates based on the Bills of Mortality gathered by the city clerks, and other sources, suggest that at least 100,000 people were killed in London, which had a population of roughly half a million at the time.\footnote{See e.g. Shrewsbury, 1971, \textit{A history of bubonic plague in the British Isles}. Cambridge University Press for a thorough analysis} That is to say, this single disease outbreak killed upwards of 20\% of the population of the capital city. Again, it is practically impossible to imagine what that must have been like for those living through this horrific experience. Certainly amongst the poor, it is hard to imagine
any Londoner who would not have lost at least one close relative to this brutal pestilence.

This time at least the planets were not blamed, though in fact the alternatives were worse. By blaming the spread of the disease on stray cats and dogs, and consequently culling them, they removed one of the ways of controlling the *true* cause of the disease – the rats which carried plague-infested fleas throughout the city. Again, if we wanted to provide evidence that scientific advances since the lifetime of Isaac Newton have saved hundreds of millions, if not billions of lives, through health and medicine alone, then this might be a good place to start.

We should return to the thread of this chapter in which, if you recall, I promised to introduce our familiar Professor Newton to the breakthroughs made in the study of disease up to the late Nineteenth century. And with this aim, the next prominent figure we should meet is Francesco Redi (1626 – 1697), whose life overlapped with that of Newton’s, and therefore gives us the best idea of the state of the art understanding of infectious disease at the point that Newton died.

Redi was a physician, born in Italy, who rapidly rose to positions of power within the potent 17th Century ruling families, becoming court physician to Ferdinand II, the Medici Grand Duke of Tuscany, and after that to his son, Cosimo III, who succeeded him. Redi’s early childhood was marred with disease when an outbreak of plague in Florence in 1630-1633 killed roughly ten thousand people.42 And it is for his work on disease that he became well known. Specifically, for his work on the theory of spontaneous generation, which had been a prominent component of disease theories thus far.

Redi questioned the prevailing theory that organisms such as maggots were spontaneously created on putrefying meat. The idea seemed odd to

him, realising that animals of a larger size never arose magically from thin air – they always had parents who would give birth to them, or eggs from which they would hatch. It seemed likely that the same was true for these smaller creatures too. So he devised a cunning experiment to test this hypothesis, by leaving pieces of meat in various locations, both open to the elements, and sealed inside glass jars.

Unsurprisingly for us, though perhaps surprisingly (and revolutionarily so) for Redi, he discovered that maggots indeed did not appear at all on meat that was protected in a sealed jar, and that meat kept in a jar partially sealed with a fine cloth, which let air in and out, but would not let insects past, also remained maggot-free. Though in this latter case, maggots appeared on the cloth instead. The meat left uncovered was rapidly infested with maggots, as we would expect.

What Redi had shown, in one remarkably simple experiment, was that the millennia-old Aristotelian view of spontaneous generation was completely wrong – at least in this one regard, and therefore probably in many other ways too, if not entirely. Just as human beings, dogs, cats, horses and cows required parents, so did maggots. If the parents (in this case, flies) could not get to the meat in order to lay their eggs in it, then the maggots would not appear.

The experiment seems so obvious to us now, but perhaps this should give us reason to think more carefully about the speed with which we rush to assumptions about historical civilisations. Redi was no idiot, and neither were his colleagues across Europe. Yet in two thousand years, nobody had thought to question the theory of spontaneous generation of maggots because it presumably hadn’t even occurred to them that it might be wrong. Such is the power of a prevailing mode of thought.

And it is the same mode of thought that blinded scientists throughout history to the possibility that disease – undoubtedly the greatest single cause of human death in the history of our species – might be caused by organisms so small that they cannot be seen with the naked eye. The
bacterium that caused the Black Death, *Yersinia pestis*, measures just 2 micrometres in length – approximately one fiftieth the *width* of a human hair. Hundreds of millions of lives were lost to this one pathogen alone, and the discovery that something so small could cause such unimaginable suffering surely never even crossed the mind of anyone involved in medicine in 17th Century. Yet Redi questioned the prevailing dogma of spontaneous generation, and over the next two centuries it gradually crumbled under the weight of scientific evidence.

One of the first to consider investigating the microscopic world was Anton van Leeuwenhoek (1632 – 1723), who also worked at the same time as Newton, though there is no evidence that the two ever met – possibly because van Leeuwenhoek made the mistake of communicating largely with Newton’s adversary Robert Hooke. Having said that, van Leeuwenhoek did enter into a voluminous communication with the Royal Society of London, where he published the recordings of his many ground-breaking microscopic studies. So it is certain that Newton would have been aware of his work.

Van Leeuwenhoek didn’t invent the microscope – that particular accolade goes back certainly to Galileo Galilei, and possibly earlier, to two of van Leeuwenhoek’s Dutch compatriots, Hans and Zacharias Jansen, in 1590. However, he certainly improved it and perfected its use in the study of microorganisms. Thus far the microscope had only been used to examine the structure of bodily tissue and plant *cells* (a term, incidentally, coined first by the same Robert Hooke in his 1665 work *Micrographia*, in which he details the first ever observations of a microorganism, namely a microfungus called *Mucor*). But van Leeuwenhoek realised that he could improve the design of even the best microscopes by creating far more precise lenses. And this advantage allowed him to explore even tinier scales, and to view finer details with greater clarity than ever before.

Van Leeuwenhoek’s first view of the microscopic world must have been even more exciting than the first time Galileo himself peered
excitedly through the eyepiece of the first telescope. What he found even in droplets of water that seemed clear to the naked eye, were countless tiny organisms, swimming erratically, eating, fighting, fleeing, dividing, dying – in short, an entire new world in miniature, seemingly magical, utterly alien and staggeringly exciting. There had been a vast, complex ecosystem of creatures living alongside the human race throughout all of history, multiplying and dying by the trillions, but nobody had known about them until that very moment when van Leeuwenhoek first peered through his newly-fashioned lens and drew into focus a seemingly innocuous droplet of water.

These observations were so profoundly shocking and so terrifyingly revolutionary that the experts in London simply refused to believe them. When van Leeuwenhoek sent over his first papers in the early 1670s, the Royal Society insisted on sending back an expert team of biologists (and a clergyman, oddly) to go and see for themselves. The Dutchman’s discoveries were, needless to say, fully vindicated, and he became a household name. And his discoveries began to set a lot of great minds thinking. After all, if there was a world of microorganisms hitherto unknown to science, hiding on microscopic scales, then what might their purpose be? What effects might they have on the macroscopic world or people, plants and animals?

The first explanations from van Leeuwenhoek himself were unsurprisingly religious – the microorganisms were simply the work of God showing off that he could create the wonders of life in miniature, rather like the work of a master sculptor. It is perhaps unsurprising that detailed analysis of the fundamental biology of bacteria forms one of the most regularly repeated (though predictably fallacious) arguments in favour of the recently popular, though now thankfully moribund form of religious creationism known as ‘Intelligent Design’. How could such exquisite creatures possibly come about? Well, as we now know, Darwin explained that in our last chapter.
In fact, van Leeuwenhoek might not have been the first to discover the microscopic world of bacteria. In 1646, the German Jesuit scholar Athanasius Kircher (1601 - 1680) published a report on the bubonic plague entitled *Scrutinium Pestis* in which he described his observations of blood taken from plague-infected patients, and the “tiny animals” that he saw within it, concluding that the plague might be spread by microorganisms. He was, of course, completely correct, though it seems that his microscope probably wasn’t powerful enough to resolve the plague-causing bacteria, and he was probably observing blood cells. However, as you will probably tire of reading during this chapter, his results were not widely read, understood or accepted.

We’ve jumped about a lot so far, having gone from the end of the 19th century at the end of the previous chapter, we have wandered back to the 14th century, and are still only just getting back to the time of the death of Newton again. But the context is highly important, as the modern understanding of disease is one of the scientific discoveries that has altered our perception of the world perhaps more than any other. To understand just how thorough this change has been, it’s important to realise where we came from – to appreciate just how profound the paucity of knowledge was in Newton’s time. Indeed, when the great man died in 1727 the state of the art was pretty much what I’ve just described – the world of the microorganism was no longer a secret, spontaneous creation looked on shaky ground, and certain scientists were beginning to wonder whether this new miniature world might perhaps have something to do with at least a few common medical conditions. But there was still a lot of work to do.

Yet despite this enticing beginning, there was little progress on the question of disease in the 18th century – presumably everyone was busy making steam engines instead. Though there was progress in the scientific methodology by which we nowadays assess the efficacy of medical interventions, and that was due to a Scottish physician called James Lind (1716 – 1794), who worked as a surgeon in the Royal Navy.
Long naval voyages were extraordinarily dangerous in the 18th Century, not just because of the risk of piracy or stormy weather, but also because of a little understood condition that was almost exclusively a disease of the Navy, and it exacted a horrifying toll on those who made their living on the high seas. This disease killed slowly, through a gradually worsening series of afflictions that lead to jaundice, tooth loss, bleeding and severe fever, all (we now know) due to the breakdown of collagen – the protein that makes our connective tissues.

In 1740, a Royal Navy Commodore by the name of George Anson (1697 – 1762) led a brave new expedition to circumnavigate the globe in search of Spanish navy vessels, which he intended to capture in the name of the British crown. During his 4 year voyage, across the eight ships of his fleet, almost nine out of every ten sailors who set out from London perished. In fact, of 1,854 crew only 188 returned to Britain alive. Some of those sailors were lost to typhus and dysentery, but the majority were killed by this same mysterious disease, known as scurvy. It was a horrendous and ignoble way to die, crying in pain, far from home, far from land, and far from loved ones. Anson’s ships returned to Britain almost as ghost vessels, such was the toll of the disease. Yet instead of being court-marshalled for this horrendous waste of human life, Anson was promoted to First Lord of the Admiralty 7 years later.

What had actually killed most of those men was unknown, though there were suggestions that scurvy could be cured, or at least slightly relieved, by consuming certain herbs and fruit. The reason for that potential solution was not well known, and the practice had not gained general acceptance in the Navy of any nation at this time. And as long as there were tens of thousands of young men with nothing better to do than throw away their lives in service to their country, then there wasn’t really any strong incentive to find a cure. This was well and truly an era before modern health and safety regulations where a slightly loose floorboard would spawn a six-month legal investigation.
James Lind, whom I briefly mentioned earlier before my digression about death on the high seas, was not amused by this grotesque loss of life. Moreover, he was a determined man and set about attempting to find out what was going on. And to do so, he designed what has come to be known as the first ever *randomised trial* in all of medicine.

What Lind did was, in retrospect (and rather like many of these great medical breakthroughs), rather obvious. He had been at sea for several months when the sailors on his boat began to show the first signs of scurvy, so he proposed to investigate the condition rigorously. He took twelve sailors showing signs of the disease, and divided them into six randomly chosen pairs. To each pair he gave a different tentative cure. The cures he chose were based on his belief, widespread at the time, that scurvy was a disease of indigestion and putrefaction, for which the prescribed antidote was an acid. So one pair got cider, another got seawater (presumably they drew the short straw), another pair got vinegar, another dilute sulphuric acid (an even shorter straw), one got a mixture of paste and barley water, and the sixth group got citrus fruit (containing citric acid). They continued to be fed on those peculiar diets, and their condition was monitored. After less than a week, the pair eating citrus fruit had been almost fully cured, and the pair taking cider had shown a slight improvement. All the others had remained just as ill or got worse.

This all seems obvious to us, of course. If you want to see what might cure a disease, the best plan would be to pick a list of possibilities and then actually go out and test them empirically. Yet apparently this was an extraordinary novelty at the time, and Lind was something of a pioneer to have tried it. The degree to which people didn’t actually seem to care about the truth behind mankind’s most important problems, I must confess, still baffles me though I would be dishonest if I claimed that this was purely an historical problem.

The most amazing part of this whole story is that, though Lind wrote up his experiment, he apparently missed its significance because he failed
to emphasise the role of citrus fruit in curing scurvy. In fact it was another half century before the idea of providing sailors with citrus fruit on long voyages actually took off, and deaths from that terrifying condition plummeted as a result. Nobody knew why citrus fruit helped so much and, in fact, the science behind that wouldn’t be discovered until the 1930s. However, it had now been established that citrus fruit did indeed cure the disease – not because they were acid, but because they provided a chemical now commonly known as vitamin C.

This vastly important ability to avoid one of the greatest dangers of 19th Century seafaring gave the already powerful British navy a huge advantage over its competitors. The reason why Britain truly ruled the waves throughout the Victorian era can be traced in part to our defeat of scurvy. Lind may not have achieved as much as he could have done with his studies of the disease, having missed its importance, though he did certainly save many lives through another route – the regulations he wrote insisting on greater cleanliness and sanitation for sailors were largely instrumental in ridding the Royal Navy of typhus.

All of which leads us nicely back to micro-organisms. Though it turns out the scurvy is purely a disease of malnutrition, typhus definitely is not. Yet by the turn of the 19th century, the medical profession was still very much in the dark about both conditions, and had not yet realised that they might belong to different categories of ailment. However, that same century heralded a succession of revolutionary studies that were to vindicate the suspicions of those few brave minds who dared to question the prevailing orthodoxy. And the first of those discoveries was made by another Italian named Agostino Bassi (1773 – 1856).

In the first half of the 19th century, a mysterious white fungus was destroying the silkworm industry in Europe, primarily in France and Italy, and causing huge financial loss. At the time, those two nations dominated trade in this highly valuable commodity, and the prospect of losing such a vast industry was causing a great deal of worry. The silkworm problem was causing interest at the highest levels of
government, and great riches were potentially in store for anyone with the wit to prevent this impending disaster.

Bassi firmly grasped that incentive, and took it upon himself to study the feared silkworm mould under a microscope to see what could be discovered. He showed that there was in fact a microorganism responsible for the disease – a fungus now known as Beauveria bassiana after its discoverer\(^{43}\). Though he had shed light on the silkworm fungus, Bassi continued to speculate that, if silkworm were being killed by such a tiny adversary, then might not animals and humans be similarly endangered?

This ground-breaking work partly built on the mildly controversial views of his mentor, Lazzaro Spallanzani (1729 – 1799), who had already put forward the view that the microscopic organisms discovered by van Leeuwenhoek might be small enough to be carried undetectably in the air, and could then settle on prospective victims before multiplying rapidly. His suggestion was that boiling could presumably kill these tiny creatures, and he conducted a series of experiments to bear this out. Bassi’s studies showed that this speculation was correct, and vindicated his former master, sadly 36 years too late for Spallanzani to bask in the glory, but just in time to rescue the ailing Italian silk industry from almost certain collapse.

I’m afraid the story doesn’t end quite as well as it could have done – the European silkworm industry was indeed rescued by Bassi’s work, though only for a few decades, after which a combination of economic and social factors pushed it into a fatally steep decline. Today, over 70% of world silk production happens in China, and most of the rest is in India. Italy isn’t even in the top ten any more. Yet Bassi’s scientific legacy lives on, because his work led to a scientific revolution in the understanding of disease.

\(^{43}\) In fact, today there has been some work in using this exact fungus as a non-specific insecticide, given the wide range of pest species it can kill.
In fact, just twenty years after Bassi published his seminal work, another remarkable study was carried out that proved once and for all that human disease could be caused by microorganisms. The year was 1854, and the place was London, England. Precisely, the Broad Street area in Soho, Central London.

Soho was a foul, insanitary place, being both heavily overcrowded and littered with overrunning cesspools. At this time, and despite the work of Bassi and all the others we have met in this chapter, the predominant theory of disease was still the miasma theory – claiming that “bad air” was responsible for the unspeakable death tolls caused by plague, typhus and cholera. It seems very difficult to accept that this was the accepted opinion barely a century and a half ago, yet such is the pace of scientific progress: there are almost certainly people alive today who knew, in their childhood, men and women who witnessed one of the most important disease outbreaks in medical history.

The story concerns the third of the three big diseases – Cholera. At precisely this time, late summer 1854, a cholera outbreak flared up in this part of London and started to take a toll on the local population. The symptoms of Cholera are brutal, with severe vomiting and diarrhoea often leading to death through dehydration and mineral imbalances. In the week and a half between 31st August and 10th September 1854, a staggering 616 people lost their lives to this horrible disease, and one man who found himself right in the middle of this revolting catastrophe was a physician by the name of John Snow (1813 – 1858).

Snow had already spent some years researching cholera, and was not remotely convinced by the “bad air” theory that remained the dominant hypothesis at the time, so he saw this outbreak as the ideal opportunity to test his ideas, and began to gather statistics on the cholera epidemic as it unfolded.
What Snow did next was extremely clever, and eventually led him to identify the true cause of the death and destruction. He did what we would now call “data collection and analysis”. The first step, he argued, was to see if there was any pattern to the disease outbreaks, so he took the locations of all the deaths and marked them with dots on a map of the area. When he did this, an extraordinary pattern began to emerge. The deaths were not evenly spaced across the map, but rather they clustered almost without exception in one small area, centred around the water pump in Broad Street. Snow continued his investigations, investigating the families of the deceased, and coming to the conclusion that

“...there has been no particular outbreak or prevalence of cholera in this part of London except among the persons who were in the habit of drinking the water of the above-mentioned pump well”\(^{44}\)

The conclusion was certain, in his mind, and he managed to convince the authorities to remove the handle from the Broad Street well pump. Within a few days, the deaths subsided, and a fuller enquiry could be carried out. Having examined the area, Snow discovered that the water pump was located right next to a cesspit that had contaminated the water supply with the faecal bacteria that were responsible for the outbreak. Though Snow never positively identified those bacteria under a microscope, to him the case was closed and the miasma theory, like those 616 unfortunate victims, was dead and buried.

Well, things are never quite that easy in science – there are always those who refuse to reject old theories even when evidence against them becomes overwhelming. Perhaps that’s a strength of science – after all, it is the last few stubborn hold-outs who force those proposing the new theory to make their case watertight and to anticipate all potential counter-arguments. Yet at the time it never seems that way.

\(^{44}\) John Snow, *Medical Times and Gazette* 9, September 23rd, 1854.
Perhaps the darkest hour of the medical community concerns the story of Ignaz Semmelweis (1818 – 1865), a remarkable Hungarian physician who discovered a secret that could have saved the lives of thousands of terrified women during childbirth, but yet whose work was so widely ignored by his colleagues that he died in an insane asylum just 18 years after it was published. His almost complete mental breakdown was likely the result of stress, overwork and a spiralling cascade of depression caused by the sheer reluctance of the medical profession to accept his unambiguous findings.

The contribution of Ignaz Semmelweis was based on observations he collected when working in the maternity clinic in the Vienna General Hospital. At the time, a shockingly large proportion of women died in childbirth – by some estimates as many as 30 percent compared to roughly 1 in 10,000 today – three thousand times fewer. Semmelweis noticed that not only was this disease rate higher for those giving birth in hospital compared with those giving birth outside hospital, but it was also much higher for births attended by trained doctors than it was for those handled by less experienced nurses. He started to think about why that might be, and after much deliberation, eventually realised the one major difference: In this particular hospital, the doctors would often perform autopsies on corpses as part of their daily tasks. Then, without much consideration, they would wander over to the maternity ward and examine the pregnant women without washing their hands.

Again, this work took place barely a century and a half ago, yet the disgust with which an educated 21st Century reader will respond to that story merely proves my point about the profound shift in perception that has taken place in a relatively short time. In the mid-19th century, the suggestion that some kind of contamination could be carried from cadavers to other patients was widely (though not universally) regarded as complete nonsense.

However, Semmelweis kicked off a cleanliness programme where the doctors were forced to wash their hands thoroughly in chlorine bleach
before examining pregnant women. It was a simple measure, and it reduced maternal deaths in childbirth due to puerperal fever by more than an order of magnitude, to around 1%. Yet the idea was so alien to the medical staff at the time that it was almost completely ignored. After Semmelweis left, the practice was dropped, and maternal deaths shot up again. A similar story was to be repeated in the hospital in Pest, Hungary, where Semmelweis continued his studies.

Semmelweis died at the tragically young age of 47, through blood poisoning probably as the result of a savage beating he received on admission to the mental asylum in 1865. Despite this pathetic, martyrly end, he is now posthumously regarded as having been one of the greatest founders of modern medical practice of cleanliness. Today he has two hospitals and a university named after him, and his findings are responsible for saving the lives of millions of young women in childbirth. If you imagine the thousands of women he saved in Vienna – from hundreds per year down to a few dozen – and then multiply that by all the hospitals in Europe – you get an idea of the impact of this one man’s courageous work. Semmelweis, sadly, never learned of the enormous good that he had achieved, but we can still celebrate his work with the profound degree of gratitude that it deserves.

So this tragic story showed that the germ theory of disease was still far from widely accepted, yet it would not be long before the work of Louis Pasteur (1822 – 1895) would finally bring to a close the primitive, superstitious medicine of old and usher in a new age of modernity. Pasteur’s work, the results of which survive today in our process of Pasteurising milk and other foodstuffs, focused on investigation of the role of microorganisms in common diseases, and how they could be effectively controlled.

Though there have been many extraordinary discoveries in this chapter, it is undoubtedly Pasteur who will emerge the hero of our story, thanks to the sheer impact of his research on the medical community, and the technologies that we rely on today. Pasteur showed beyond any
reasonably doubt that not only were many phenomena, including several common and regularly fatal diseases, caused by the spread of microorganisms, but he also showed how many of these diseases could be prevented entirely by the practice of vaccination.

The core discoveries of Pasteur’s life can be summarised with two discoveries. Firstly, he continued the work of Francesco Redi by demonstrating that bacteria would only grow within isolated flasks when they were allowed access to the air, showing that the seed material for the bacterial growth was airborne, and was not spontaneously generated within the medium itself. He proposed a method for preventing micro-organisms from spoiling food and drink, by heating the liquids briefly beforehand. This process is now known as Pasteurisation in his honour.

Secondly, just like Redi, Pasteur realised that, if spontaneous generation was nonsense, and if tiny particles in the air could cause milk and beer to spoil, and could cause bacterial and fungal growth in his experimental flasks, then maybe airborne particles were also responsible for human disease. And at last, the world listened. The realisation that Pasteur had unleashed was a startling one – not only was there a microscopic world of bacteria living in pond water, as first glimpsed by Boyle and Van Leeuwenhoek in the 17th century, but in fact those tiny creatures were all around us, in every droplet of water, in every gulp of air – the world is full of an unimaginable multitude of microscopic entities that had been living their lives all around, and within us completely undetected for all of human history.

The obvious conclusion of Pasteur’s work, taken forward by celebrated names such as Joseph Lister (1827 – 1912), amongst others, was that cleanliness was the best way to combat a whole range of diseases. And the change in medical standards was rapid and effective. But Pasteur had another contribution to make, and this was equally important. This time he built on the foundation of the British physician, Edward Jenner (1749 – 1823). We skipped past Jenner without a mention earlier, but his
story suddenly becomes relevant at this point. Jenner had discovered something extraordinary important, though he didn’t have the knowledge or the time to take it to the conclusion that Pasteur was able to reach. And it concerns a disease that, today, is completely unknown yet in its time struck terror into the heart.

Smallpox was a horrific, scarring disease, which debilitated and disfigured many a citizen of the 18th century. It caused a horrific rash followed by grotesque, unsightly blisters over the whole body. It was fatal in about one case in three. Estimates vary, though rough calculations of the death toll from smallpox in the twentieth century alone generally exceed 300 million worldwide and may have reached as many as half a billion\(^\text{45}\). The fact that you will never have seen a case of this disease in your life speaks volumes for the progress that we have made as a human species.

Pasteur was the one who perfected the method by which smallpox was eradicated, though Jenner was really the first to come up with the idea behind it. And it was a simple idea, based on the strange observation that milkmaids seemed to be more or less immune to the disease. And the correlation was so striking that Jenner decided to work out why it might be. He realised, after some research, that most milkmaids had instead caught a related, but much less dangerous, disease called *cowpox*. For some reason\(^\text{46}\) those people who had caught, and recovered from, cowpox seemed to be immune to the much more serious smallpox. It was a tremendous breakthrough.

Jenner was keen to prove that his hypothesis was correct, and began by deliberately infecting a young boy named James Phipps with the cowpox disease. Once the boy recovered, after a short illness, he proved to be completely immune to smallpox when presented with that more deadly disease on a separate occasion. Jenner, elated, continued to roll


\(^{46}\) Jenner provided some speculations that turned out to be inaccurate.
out his *inoculations* to a wider audience and what followed was one of the greatest revolutions in medical history.

So great was the effect of Jenner’s discovery that 183 years later, on 9th December 1979, the World Health Organisation officially declared the smallpox disease totally *eradicated* from the human race.

It is worth pausing and contemplating that statement, because it describes one of the greatest achievements that our species has ever accomplished. Smallpox, this horrific curse on humanity, this barbaric executioner and disfiguring assassin – no longer exists – it was eradicated by science – the sole example of a beneficial man-made extinction.

One might argue that most medicine up to the early 19th Century was doing more harm than good. We heard the story of Ignaz Semmelweis where this was literally true – mothers giving birth with trained doctors on hand were more likely to die than those who gave birth at home. So it should come as no surprise that this point in time provides the origin for lots of fashionable alternative medicinal practices. Because doing pretty much anything else – no matter how wacky – was preferable to going to a hospital in 1800.

Some of those pseudoscientific practices survive today, though mercifully few. Quite why some survive and others don’t is probably more a factor of social and political support than anything else. Many took inspiration from Jenner’s work, such as the idea of homeopathy, loosely based around the concept of “like cures like” that Jenner seemed to have showed. Despite the fact that it has been comprehensively disproved, and its mechanism of action is now known to be nonsensical, still some homeopathic practitioners continue to peddle their quackery

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47 Having said that, scientists are currently on the verge of declaring that polio, an acute paralysing viral infection, has been similarly eradicated thanks to a huge, worldwide effort.

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even in the 21\textsuperscript{st} Century. It is one of the few remaining fossils of an age before scientific medicine, and offers a glimpse into a long disappeared world.

Perhaps ironically, Jenner, Snow and Pasteur all died as the result of strokes – a purely physiological condition caused by a lack of blood flow in the brain, and nothing to do with microorganisms. Pasteur, having laid the foundation for all of modern medicine, passed away in 1895. He has a research institute and a University named after him in Strasbourg, as well as numerous medical schools and hospitals around the world. Pasteur’s work on immunisation may have saved more human lives than any other discovery in the history of the human species, which is quite a claim to fame. It’s difficult to calculate the impact of the discovery of germ theory, and I’m not sure how to estimate the deaths that have since been avoided by modern medical cleanliness, but to guess a number in the order of a few billion would probably not be far wrong.

If you need any proof that science has advanced the human condition, and the information in this chapter so far has not swayed you, then perhaps dwell on the story of the Bubonic plague that we mentioned earlier – a disease that wiped out probably hundreds of millions of human beings over the last few millennia. Yet, as we have seen, it was caused by a bacterium called \textit{Yersinia pestis}, which is so small that it can’t be seen with the naked eye. And thanks to science, we now know that this particular microscopic assassin has precisely 4,653,728 base pairs in its genome (strain CO92)\textsuperscript{48}, and can today be cured by a handful of doxycycline pills costing a few pence each. After the plague devastated 14\textsuperscript{th} century civilisation it took at least a century and a half for the world’s population to recover. Nowadays, Bubonic plague need never cause us any trouble ever again.

The advances made by medicine in the 19\textsuperscript{th} century caused extraordinary improvements in human welfare. We had learned how to

\textsuperscript{48} http://www.sanger.ac.uk/resources/downloads/bacteria/yersinia.html

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synthesise chemicals that could justifiably be seen as the cure to diseases that had plagued humanity for its entire existence. Yet the idea of chemicals granting hitherto unknown medical benefits was not a new one – in fact Newton believed, as did many of his colleagues, that were he to find the correct mixture of chemicals, and the correct way to prepare them, then he might even discover a far greater and even more valuable secret – the secret to eternal life. And this is where our tale takes us next.
The Death of Alchemy

“A man may imagine things that are false, but he can only understand things that are true, for if the things be false, the apprehension of them is not understanding.”

Newton

Though it is now accepted that the Americas were first discovered by Europeans in the 11th Century expeditions of Norse explorer Leif Ericson, the modern story of that vast continent begins in earnest with the intrepid 1492 voyage of Christopher Columbus (1451 – 1506), who kick-started one of the most important migrations in the history of our species. What enticed those first explorers and conquistadors was not merely the sheer exhilaration of setting foot on a newly-discovered continent, covered in hitherto unknown flora and fauna, but also the dreams of riches that might be discovered deep within the jungle cities of its mysterious native inhabitants.

Columbus returned a second time to the New World in 1493, with a fleet consisting of seventeen ships, laden with men and supplies. They set out from Cadiz with the aim of further exploring this enigmatic continent and establishing permanent settlements for the glory of the Crown of Castile. One of the adventurers joining Columbus for this voyage of discovery was a nineteen year-old Spaniard by the name of Juan Ponce de Léon. Young Juan was a decorated soldier who, no doubt, hoped that this hazardous journey would bring him power and riches beyond any he could have obtained in Europe at the time.
On 3rd November 1493, after nearly six weeks at sea, the fleet arrived at an unknown island in the region now known as the Lesser Antilles, and Columbus christened it Dominica. Continuing along the archipelago, the fleet followed a north-westerly arc up past Hispaniola and Jamaica towards Cuba before returning back along the same route and eventually departing for the return journey to Spain. However, Ponce de Léon had other plans and he disembarked in the Caribbean together with a contingent of Spanish soldiers. There he lived for most of the rest of his life, rising quickly through the ranks, becoming governor of the province of Higüey in Hispaniola in 1504, and then being appointed the first governor of Puerto Rico in 1509. It was from this stronghold that he launched his famous expeditions northwards. Those same expeditions inspired an intriguing legend that persist to this day.

Ponce de Léon first sighted the coast of Florida in early April 1513. He had been promised governorship of any new lands he discovered, so funded this sizeable expedition from his own personal wealth. Yet according to later legend there were other reasons why he was so keen to explore northwards, and they had nothing to do with money or power. Florida, so the legends said, was home to the one thing more valuable than either wealth or political clout – it was the source of the Fountain of Youth, the spring whose crystal waters bestowed the gift of eternal life.

Whether or not Ponce de Léon actually knew or believed these legends is uncertain. Most historians believe that the tales were attached to his name posthumously, perhaps for political reasons. He certainly never wrote about such a quest, though it is possible that he wanted to keep his secret out of sight from prying eyes. Either way, no such spring was to be found and Ponce de Léon met an ironically untimely end in 1521 when, during a battle with native Floridian warriors, he was struck with a poisoned arrow. He died of the wounds a few days later aged 47 years.
There is not, nor has there ever been, a literal fountain of youth on Earth. Especially not in Florida, though it does have one of the highest median ages of any US State. Yet the quest for eternal life represents the embodiment of a dream that humanity has pursued since our species first drew breath, and each accumulated failure has merely inspired those seeking this ultimate goal to try even harder than before. In the late 17th Century, some were becoming convinced that this new resurgence of *Natural Philosophy* might hold the key to discovering the *elixir of life* – a mythical potion whose taste would bestow immortality on its drinker. And this was a quest that Isaac Newton, with his extraordinary intellectual talents and his gift for experimentation, felt himself uniquely qualified to attempt.

Newton’s secret interest in alchemy was only really discovered in the twentieth century when historians began to search through his personal notebooks. The depth of his obsession with these covert arts amazed and confused those who had grown accustomed to thinking of him as a practical, down-to-earth experimenter. Yet this same cult-like superstition also proved extremely popular amongst several of the most prominent Renaissance thinkers. Adherents included Elias Ashmole, founder of Oxford’s famous Ashmolean Museum; Tycho Brahe, famed Danish astronomer of the 16th Century, who defended the Heliocentrism of Nicolaus Copernicus through meticulous naked-eye observation of celestial objects; and even Robert Boyle, Newton’s contemporary and one of the founders of modern Chemistry.

The ultimate goals of alchemy, understandably attractive to an impoverished seventeenth century scientist, were twofold. Firstly, the possibility of discovering the elixir of life which could grant immortality to its drinker and fabulous wealth to its discoverer; and secondly, the hope that one might discover how to transmute cheap, common elements such as lead and iron, into vastly more valuable ones like gold.
Of course, with the benefit of several centuries of progress and from the knowledge of 21st Century chemistry and biology, we know that the quest was destined to fail – at least with the apparatus and techniques available to Newton and his contemporaries. Yet with modern science, as we will see in later chapters, we seem to be returning time and time again to the magic of the ancients and showing how, in a certain sense, a lot of it was actually not far from the truth.

But it’s important to realise that there has been a very significant shift in our understanding of chemistry since Newton’s day. As we examined in the first chapter, much of science in Newton’s time was based around the beliefs of the ancient Greeks who claimed that all things were composed of a mix of the four basic elements: Earth, Air, Fire and Water. This theory was still being taught at Cambridge even in Newton’s time, though this was set to change as Newton’s unification of classical physics into simple laws based on one single innate property of matter – mass – soon eradicated the old status quo.

Yet the Ancient Greeks had another idea concerning matter which had been largely ignored in Natural Science during the time of Newton – namely the belief of the Atomists led by Democritus in the 5th Century BCE. And one of the questions that interested this extraordinary group of thinkers was to ask what would happen if one were to take a certain substance – say, an apple - and continue cutting it in half over and over again. If a sufficiently precise scalpel could be created, could this process be continued for as long as one desired, or was there some limit – some end state that could not be further subdivided? This hypothetical residue was called the atom (ατομος), from the Greek : a- (negative prefix), temnein (to cut). Hence an “uncuttable” fragment of matter.

The concept of the atom had lain undisturbed for almost two millennia, though in the late 18th and early 19th centuries it appeared on the scene once more, in a form that would have been almost unrecognisable to Democritus and the classical atomist school. Yet this ancient theory had suddenly become necessary to explain away some of the unexpected
and troubling results that were being uncovered in laboratories across Europe.

The story of Chemistry begins in 18th Century France, a country soon to be plunged into turmoil as resentment of the ineffective ruling elite boiled over into class warfare and bloodthirsty civil upheaval. Antoine Lavoisier (1743 – 1794) found himself very much on the wrong side of that violent class struggle, born into a wealthy family and surrounded by opulence throughout his youth. He was 45 years old when the revolution began, and a mere five years later, on 8th May 1794, he was executed by guillotine after being corruptly convicted of a demonstrably false accusation. Yet in that short life, Lavoisier laid the foundation for modern chemistry.

Lavoisier discovered several extraordinary truths that earned him his place in history. So pervasive is our modern understanding of chemistry that these may seem self-evident to you, but that says a great deal more about the extent to which science has progressed in two and a half centuries rather than about the particular merits of your (undoubtedly formidable) mind.

Perhaps Lavoisier’s most influential discovery was his law of Conservation of Mass. The principle is fairly simple and, as it happens, not quite true as we move into modern physics – but it’s good enough for now. It simply states that, during a chemical reaction, if you measure the mass of all the chemicals going in, and the mass of all the products coming out, then you should always find that the total mass has not changed. That is to say, no matter is created or destroyed in chemical reactions – it just gets moved between different forms. Lavoisier published this theory in his 1789 book “An Elementary Treatise on Chemistry”, which also put forward another of his most controversial demonstrations, that of the non-existence of Phlogiston.

Let me backtrack a bit and introduce you to one of the most widely accepted fictions of the 18th Century. It might seem obvious to our 21st
Century minds, but before Lavoisier’s work arrived, nobody really understood why flammable things burned. Everyone knew that a burning material lost weight as it was consumed by the fire, though inevitably it left behind a residue of ash. Clearly some component of the fuel was lost during the burning process, and this lost substance was obviously combustible, as the remaining ash would no longer burn without it. Not knowing anything else, the scientists decided to name this speculative substance Phlogiston, and it rapidly became the leading hypothesis for the cause of combustion. When a piece of coal burns, it was thought that Phlogiston was being released in the flame. Further studies were performed to show that a burning ember placed inside an airtight jar would burn for some time before gradually being extinguished. The obvious conclusion was that the air had maximised its capacity for absorbing Phlogiston and so no more could be released, and hence the fire had to cease.

Two hundred years later, the American historian and philosopher of science, Thomas Kuhn (1922 - 1996), would write a ground-breaking work entitled “The Structure of Scientific Revolutions”, published in 1962. The thesis to his work was that science progresses in disjoint periods of constructive and destructive development. In the former, work is done to elaborate and expand the prevailing scientific theories within the framework that they present. In the latter, accumulated evidence highlighting the flaws in those same established beliefs eventually becomes so fatal to the old theory that it results in their destruction, allowing them to be replaced with something new, and often strikingly different.

In a sense, every chapter in this book (with a few exceptions) represents such a paradigm shift – from an old model to a new one, replacing an entire framework of understanding. Yet the Phlogiston theory is perhaps one of the best examples of all, as it demonstrates so clearly how scientific progress must occasionally consist of as many steps backwards as forwards, if eventual progress is to be made.
The Phlogiston theory was wildly successful. Not only did it explain why materials lost mass when they burned, and why they stopped burning when placed in a sealed jar, but it explained a number of other phenomena, too. For example, when combustion occurs in a sealed jar, not only does the flame eventually die out before the fuel is consumed, but the volume of air is apparently reduced. To modern science, the reason for this is known, but the Phlogiston theory could also be fitted to this discovery, too: The release of Phlogiston simply spoiled the elasticity of the air, making it less springy, and hence reducing its volume.

Yet as more studies were done, these peculiar observations started building up. Some could be slotted, albeit rather precariously, into the Phlogiston theory, but others were more difficult to explain. Many metals, for example, actually increase in mass when burned. It was hard to make the theory fit with such a glaring exception.

Phlogiston theory was ably defended by no less a mind than Joseph Priestley (1733 – 1804), who discovered some of the same phenomena that Lavoisier later explained, but was so absorbed by the Phlogiston theory that he failed to recognise those observations for what they were. On discovering that certain reactions produced a different kind of air that permitted greater amounts of combustion, Priestley erroneously concluded that this air must be “de-Phlogistated”, so that its capacity for Phlogiston was increased.

Lavoisier however recognised the signs – the growing list of anomalies that all seemed to go against the prevailing consensus – and he knew that this was going to spell the end for the Phlogiston theory before long. He felt sure that there was a better way to see what was going on, and it turned out that this better way was the foundation of the modern science of Chemistry. He showed that the entire scientific community had the whole picture upside-down – combustion was not caused by the emission of a substance into the air, but rather by the reaction of the
fuel with another substance from the air. And that substance he named “Oxygen”.

Suddenly, everything slotted into place. The reason why fires were extinguished in sealed containers was that the air ran out of Oxygen. The volume of gas inside decreased because the Oxygen gas has a lower density than the other substances formed after combustion. The reason why metals such as Iron gained weight when they rusted was because they reacted with this Oxygen to form substances called Oxides, which weighed more than the metal alone.

In many ways, this extraordinary shift in perception mirrored the work done before Newton’s birth by Copernicus, who showed that the whole picture of the Solar System was so much simpler if, instead of attempting to build complex mathematical models for how the planets moved in cycles-upon-cycles through space, one simply realised that the Sun was at the centre and everything revolved around it.

Lavoisier’s correct understanding of Oxygen led to his identification of a number of other important chemicals including Hydrogen, and to the realisation that Hydrogen and Oxygen together formed water. The fact that water could be the product of the mixture of two invisible gases must have been a staggering revelation, but Lavoisier’s experimentation showed it to be true. In fact, the name Hydrogen comes from the Greek for water (Hydro-) and the stem ‘gen’, which forms the basis for words such as ‘generate’ and ‘genesis’. That is to say, Hydrogen is a gas which is ‘water-forming’. Similarly, Oxygen means “acid forming” because Lavoisier believed that Oxygen was an essential ingredient in the formation of acids. This turns out not to be strictly true, but the name stuck.

Lavoisier went on to show that air itself was a mixture of different fundamental chemicals including Oxygen and, more importantly, Nitrogen (which makes up almost 80% of Earth’s atmosphere by volume). He also showed that the act of respiration (that is, the process
by which animals generate energy) is essentially a form of combustion, where Oxygen is taken in, it combines with a fuel, and this generates energy for bodies to use. Our bodies are essentially furnaces and we generate heat at approximately the same rate as a large television.

This new vocabulary of Chemistry caused an explosion of development in the subject, with scientists now thinking of all substances in terms of their fundamental building blocks, and scrambling to work out what those building blocks might be. Lavoisier showed that even the same chemical, in different configurations, could possess wildly different properties. The element carbon, for example, can be found as graphite, coal and diamond. Lavoisier didn’t know why that might be – though we shall get to that very soon.

The loss of Antoine Lavoisier stands out as one of the most horrendous wastes of human genius in history. That such a prodigious talent could be so trivially erased by power-hungry fanatics makes me shudder – largely because one wonders which other minds were similarly erased before they even had a chance to shine. One might speculate what such a great man could have achieved were he to have lived another decade or two. Sadly, he is certainly not the only great scientist about which we could pose this question. I might even be tempted to draw an analogy between Lavoisier’s foundational work in the field of chemistry, and the fall of the ancient Greek civilisation, amongst whose products was the atomic theory that his work would eventually bring back into focus.

For centuries, the accumulated wisdom of the ancient Greeks was thought to embody the perfection of the human mind – not just during the lifetime of that extraordinary civilisation, but also afterwards, long after that extraordinary engine of philosophical and artistic progress had been brutally suppressed in the Peloponnesian wars and subdued by the subsequent Roman conquest.

The day before Lavoisier’s execution, the bloodthirsty revolutionary leader Maximilien Robespierre (1758 – 1794) had given a speech
outlining his religious plans, that France should be converted from its ancestral Catholicism – the religion held by Lavoisier and much of the moribund aristocracy – to a new form of deism which he termed “Culte de l'Être suprême” (Cult of the Supreme Being). This form of deism reminded many of the paganism practiced by many of the Ancient Greeks, who Robespierre probably wished to imitate. His ideas were very short lived. Robespierre, who probably personally ordered the execution of Lavoisier, was himself executed in the same manner barely two months later.

Yet the thoughts of the ancient Greeks lived on, and atomic theory survived to see its renaissance after two dormant millennia. The works of Lavoisier also survived after his death, and now he is regarded as one of the most important founders of modern science, and the father of modern Chemistry. The irony of the entire story being that Lavoisier was posthumously exonerated just 18 months after his execution, as new evidence arose to prove that he was innocent of the crimes with which he had been accused. Scant consolation to his widow, of course, but a powerful argument against the death penalty with its gruesome and irreversibly destructive finality.

Lavoisier’s contemporary and compatriot, Joseph-Louis Lagrange, summed up the entire disgraceful tragedy perhaps better than anyone else, when he wrote “It took them just an instant to sever his head, but France may not produce another of such quality in a century.”49 He, too, was wrong of course – Louis Pasteur was born just 28 years later.

Yet with the death of Lavoisier, the future of chemistry was transferred to many other capable hands. A huge number of discoveries mark the next few decades, all pointing towards a new united theory of Chemistry based on the atomic theory – the idea that any object can be broken down into smaller and smaller constituents until one reaches an indivisible atom, the building blocks out of which all Chemistry is constructed.

49 Henry Guerlac, “Antoine-Laurent Lavoisier – Chemist and Revolutionary” 137
The most prominent figure to carry the baton onwards is John Dalton (1766 – 1844), who developed Lavoisier’s ideas in many directions and expanded on the foundations of this new science. Dalton’s main contribution to the field was his investigation into the way in which different chemicals interact, showing that they do so in fixed ratios depending on innate physical characteristics of the atoms themselves. Dalton’s exact formulation of this mechanism wasn’t quite correct, but he did come up with a number of core truths that were to define the path of Chemistry from that moment onwards.

Firstly, he proposed that all matter was composed of atoms – much as the ancient Greek atomists had suggested. He further agreed with those same Greeks that these atoms were indivisible, and all such atoms of a given substance were identical. Yet he managed to expand the theory of Chemistry way beyond the speculation of the ancient philosophers by his next claim – that the different substances he studied had atoms of different masses and sizes, and that some quality of these atoms caused all the many different properties of the substances they formed.

So far so good, but Dalton hadn’t quite finished yet, because he also investigated the process of chemical reactions, which is where he came up with the even more important discovery, now known as the “Law of Multiple Proportions”. In short, Dalton noted that, when reacting substances together, they generally combined in ratios that were suspiciously simple fractions – far more often than could be expected by chance alone.

Let’s take an example. Pairs of chemicals often form more than one compound between them. Let’s take, for example, Carbon and Oxygen, which form both Carbon Monoxide and Carbon Dioxide. In this case, a fixed proportion of Carbon would take in a certain mass of Oxygen to form Carbon Monoxide, and exactly twice this amount to form Carbon Dioxide. Dalton’s theory suggested that this was because the chemicals were formed by combinations of atoms in simple quantities. Of course
there was no *a priori* reason why this should have been the case – and it
could easily have been found that atoms could mix in any ratio they
wished, and the exact proportions of atom A to atom B affected the
properties of the mixture in a continuously varying manner. That *could*
have been true, but it wasn’t.

We now know that Carbon Monoxide is formed of exactly equal
numbers of Carbon and Oxygen atoms joined in pairs. In Carbon
Dioxide, each Carbon atom is instead joined to two Oxygen atoms.
Dalton derived the 1:1 ratio, and hence the formula “CO”, from
experimental methods and a bit of guesswork, which meant that his
results weren’t always tremendously accurate. The relative weights of
some of the most common elements were published in his work “A
New System of Chemical Philosophy” in 1808. He used Hydrogen as a
benchmark of 1, being the lightest element, but the remainder of his list
deviates quite markedly from the sort of numbers that we would accept
today. For example, Carbon was given a mass of 5 instead of 12;
Oxygen was 7 instead of 16; Phosphorous was 9 instead of 31.

Dalton also confused slightly the distinction between *elements* and
*compounds*. A chemical element is a substance made from only one
type of atom, as opposed to a compound made from two or more
different types of atom. For example, Carbon is an element as it
contains only one type of atom – the carbon atom. Yet Carbon
Monoxide is made from equal numbers of Carbon and Oxygen atoms.
Common table salt (Sodium Chloride) is made from equal numbers of
Sodium and Chlorine atoms.

Dalton was, of course, aware that some chemicals were formed by
combining other chemicals and distinguished “simple atoms” from
“compound atoms”, the latter being what we would now call molecules
i.e. groups of two or more individual atoms, perhaps of different types,
held together by nuclear forces. He hadn’t realised that some of the
chemicals he assumed to be pure elements were in fact compounds,
such as Soda (Sodium Carbonate) and Potash (Potassium Carbonate), so
treated them as if they were the same ‘kind of thing’ as elements such as Carbon and Oxygen.

Yet Dalton’s achievement, though woefully inaccurate by modern standards, was in fact an astounding feat for his day and of extraordinary importance for the flourishing subject of atomic theory. He provided a framework sufficient for those who came after him to ‘fill in the gaps’ and to expand his first tentative forays into the entire atomic theory which forms the basis of modern Chemistry.

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There are many other characters I could have included in this chapter, but one particularly stands out in my mind as worthy of a few moments of our time. In fact, this is a man whose works Isaac Newton would have known intimately, because they encapsulate the philosophical debate around the centuries-old subject of alchemy and its modern-day equivalents, and how they fit into the picture of science itself.

Francis Bacon (1561 - 1626) is another of the prominent men of history whose likeness sits alongside that of Isaac Newton in the chapel of Trinity College, Cambridge. He lived and died before Newton’s birth, born into a wealthy family of the London elite, son of a prominent politician in the court of Queen Elizabeth I. From an early age he excelled himself above his peers, going up to study in Cambridge at the precocious age of twelve (!), and then entering Gray’s Inn as a trainee barrister aged just fifteen. In fact, such was the breadth of his talents that a popular conspiracy theory of the late 19th century proposed that Bacon might have been the true author of the works attributed to William Shakespeare.

Bacon trained as a lawyer, and later took up politics, before moving into the sphere of learning for which he would become famous – the
philosophy of science\textsuperscript{50}. To Bacon, the most important project to which he could devote his extraordinary intellect was that of building up a process – a \textit{method} – by which scientific investigations could be conducted. The study of the natural world still had a reputation as something of an amusing diversion – an admittedly agreeable pastime that the educated gentleman could pursue, but not necessarily a valued career to which one could dedicate a life’s work. Real men were lawyers, politicians or clergymen.

Yet Bacon was able to ignore the conventional thinking of his time and saw science as a process by which we could improve the condition of humanity. He knew that such a valuable activity deserved a carefully devised framework within which to work. To claim that we should overhaul the way we investigated the cosmos was a risky move for the late 16\textsuperscript{th} Century. Not only had the dominant force of Aristotelian learning been firmly established for thousands of years, but also the concept that we should aim to understand the laws of science and to peer into the mind of God for our own benefit and improvement, suggested that perhaps the mere contemplation of theology and religious devotion was not sufficient for the well-being of humankind.

Yet the opinion of those around him was not of great concern to Francis Bacon. He was the first great scientist publicly to speak out against the assumptions of Aristotelian philosophy, and in doing so began to build an environment at Trinity College where Newton would later apply his own extraordinary talents to forge a new theory of physics. Bacon espoused many of his views in his 1605 work \textit{The Advancement of Learning}, here talking about the “errors and vanities” that he believed held back academic thought. One of those was the pursuit of analytic thought that so dominated academic discourse at the time, but without any recourse to actual physical investigation which would prove so important in the foundation of chemistry.

\textsuperscript{50} Bacon would not have used the word “science”, which wasn’t coined until the 1830s, but I use it here for clarity.
“For the wit and mind of man, if it work upon matter, which is the contemplation of the creatures of God, worketh according to the stuff and is limited thereby; but if it work upon itself, as the spider worketh his web, then it is endless, and brings forth indeed cobwebs of learning, admirable for the fineness of thread and work, but of no substance or profit.”

Bacon was the first to put forward the concept of empiricism – the belief that scientific hypotheses should be backed up with cold, hard experimental facts. Again, it is a view that would drive Newton away from mere contemplation of the laws of nature, and towards designing and carrying out his very own experiments to investigate the nature of the physical laws first-hand.

Ultimately the empirical pursuit of natural philosophy didn’t work out too well for Bacon himself, however, as he met an untimely end as the result of an experiment gone wrong. One winter he had the idea of investigating whether or not snow could be used to preserve meat. Unfortunately the snow had much the same effect on Bacon (the man, not the meat) as it had on the chicken he was examining, namely, it froze him and he contracted pneumonia. A few weeks later, he died.

In terms of forming the methodology for scientific thought, there are few more prominent contributors to the discipline than Francis Bacon. In the end, his legacy stands apart from those of his peers, and his influence is still felt today through the scientific method that he helped to forge. As he himself put it, “The monuments of wit survive the monuments of power.”

Indeed, it is with Bacon’s book “The Advancement of Learning” that I want to continue this tale, because it asks (and attempts to answer) some prominent questions that I think all scientists have had to wrestle with at one stage or another. As far as Newton goes, we might be

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51 Francis Bacon, “The Advancement of Learning”, IV (5)
tempted to phrase it like this: “Why did one of the greatest minds that
the human race has ever produced waste half his life in a completely
fruitless quest to transmute elements through mystic spells and
incantations?” More importantly, can we criticise him for doing so, or
would a more sympathetic investigation help us to understand why
Newton took such an unlikely course?

Frustrating though it is that Newton wasted so much time on topics that
we now know to be nonsensical, his work did at least deliver some
benefits in building the foundations for the careful chemical
experimentation that Dalton and the like would employ a century later.
However, we can’t help but mourn the waste of talent that could have
been spent extending his Principia or investigating the nature of light,
matter or even electricity.

Yet Newton spent decades studying alchemy with no success
whatsoever. What was it that led him to carry on even in the face of
such continued and unrelenting failure? Newton might have had a line
from Francis Bacon’s magnum opus at the back of his mind during this
time:

“They are ill discoverers that think there is no land, when
they can see nothing but sea.”52

Bacon’s thoughts here touch on an area of science that is at the heart of
endless heated debate in the popular press. How should we treat
pseudoscientific ideas and superstitions in our world, and what is the
role of evidence in scientific research? Pretty much every
pseudoscientific belief, from crystal healing to telepathy to crop circles,
cowers behind the mistaken retort that scientific research fosters
‘closed-mindedness’. Scientists are apparently unable to welcome new
and exciting possibilities because they are too absorbed with their pre-
existing biases. Or at least, so the argument goes.

52 Francis Bacon, “The Advancement of Learning, Book II, vii, 5
Bacon’s work probes this deep question - When is it reasonable to conclude that a claim is false, given only a lack of positive evidence in its favour? Put in more familiar terms, when is absence of evidence sufficient to provide evidence of absence?

You may have heard that second claim quite often – usually concerning a fringe belief or implausible claim. “Just because there is no definite proof of my claim, that doesn’t mean that it is false”. Take, for example, the popular example that “all swans are white”. Certainly a man of Bacon’s time would have seen no counter-examples in Britain, and I dare say that nobody in Europe could have seriously claimed otherwise. So if someone had approached Bacon with the claim that some swans are black, what response should he have given? I imagine that few people would blame him for rejecting the claim outright, never having ever seen a swan that was not white, and having seen many thousands of swans that were all white. Yet, as the story continues, there were indeed black swans in Australia, and actually in zoos across the world nowadays. So they do actually exist – they’re just very rare.

Fig. 3 : Black swans in the garden of Chartwell Manor, Kent, England.

Science can help us out with this question, because it provides us with a framework for assessing the probability that a claim is correct given all the evidence that we have acquired. We met Bayes’ Theorem in our chapter on steam power and the Industrial Revolution. To recap, this
nifty bit of logic shows us how to adjust the plausibility of any claim, given our existing knowledge and any new evidence with which we are presented. We take our existing knowledge as a starting point, then we modify that estimate by considering the degree to which the new evidence fits our theory, and the degree to which the new evidence is specific to our theory (and, hence, doesn’t fit other competing theories). From these three quantities, simply combined, we discover the level of confidence that we should have in any claim. It is a remarkably powerful tool, and shreds pseudoscience like a scythe. The only drawback is that it is sufficiently mathematical\(^53\) that it hasn’t really permeated common usage.

But we can at least address here the claim that absence of evidence cannot provide evidence of absence – and we can reject it outright. Let’s say that I were to tell you that I have a pet mammoth. My mammoth follows me everywhere I go, and he is the size of a small truck, and weighs four tonnes. Let’s say you visited my house, and I told you this story and said “oh, he’s about somewhere. You will find him if you look hard enough”. Understandably sceptical, you have a wander around my house and see nothing unusual – no four tonne quadrupeds, no broken furniture, no piles of dung, no snapped door handles. You hear no loud clomping of feet, no bellowing. You smell no musky mammoth scent and spot no prehensile trunks disappearing behind the sofa. You come back to see me again downstairs, and announce that you don’t believe that I have a pet mammoth. My reply? “Well just because you haven’t found any evidence for him yet, that doesn’t mean that he doesn’t exist!”

I presume you would be suitably unimpressed by my argument.

What’s the difference here? Why are we not justified in claiming that all swans are white, having seen thousands of them, yet we are fully

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53 The formula is remarkably simple, but perhaps looks slightly frightening until explained. I recommend you search for a good introduction to this fascinating branch of mathematics online. I have published a simple lecture on the subject on YouTube.
justified in rejecting my claim of having a pet mammoth? The difference is simple – we have to ask ourselves whether we would expect to have found any evidence were the claim actually true.

In the case of the mammoth, all those things you looked for would be pretty obvious if a pet mammoth were actually living in my house. Even if it were hiding in a back room, at very least you would detect signs of its presence. The fact that you found no evidence of those signs provides extremely strong evidence that the mammoth doesn’t exist at all. However, with the swans it is well known that different continents have different populations of animals, sometimes very different from those in the rest of the world. For example, a biologist of Bacon’s time could have convincingly argued that all mammals give birth to live young. But then in 1798 explorers in Australia discovered the duck-billed platypus – a mammal that lays eggs.

So even though we had seen all swans in the UK, or even in Europe, and they were all white, there is a reasonable possibility that swans might have evolved in different circumstances on different continents, and hence might be a different colour.

So what would I be justified in saying in this case? Well, for a start, I would be justified in making a claim about swans in Britain or Europe, because that was where I gathered my data. Not, perhaps, that they were all white, but at least that non-white swans were extremely rare in that part of the world. Copying that strategy into the field of pseudoscience, what are we justified in saying in the face of arguments from those who claim supernatural powers, or try to peddle dodgy medical remedies? One has to say: what evidence would I expect to see if this extraordinary claim were true? Then you ask yourself if such evidence actually exists, and make a judgement on that basis.

So let’s suggest that someone claimed that they could move objects by the power of their mind – the ability of telekinesis. I would expect to see a demonstration of this that showed a clear and measurable effect.
That demonstration wouldn’t involve blindfolds or hiding objects under mysterious sheets or anything like that. It wouldn’t involve darkness, any kind of elaborate apparatus or showmanship. The demonstration should be possible with any object of a suitable mass, including one that I provided myself. Absent that kind of evidence, then I would have to conclude that the natural explanation – that the claimant was lying or delusional – would be far more likely. Why? Because Bayes’ theorem tells us that an extraordinary claim – that is, one with a very low prior probability – requires extraordinary evidence.

So with alchemy, was it reasonable to assume that Newton’s failure to transmute base metals into gold was sufficient proof that it was not possible to do so? What of perseverance and optimism? Was Newton delusional to continue as he did when his results were consistently negative? Obviously so in retrospect, but that’s the view from our privileged position, armed with the understanding of 21st Century science.

The simple fact is that Alchemy did not lack plausibility from the point of view of late-17th Century natural philosophy, and Newton’s lack of success was by no means a conclusive proof that no success was possible.

To some degree, Newton probably saw his alchemical works as another avenue of exploration by which he could continue to uncover the secrets of the Universe – it was all about working out how the natural world functioned on a deep level. In his eyes, the secretive incantations of the alchemical process could very well have formed part of that picture, and Newton had no convincing evidence that they would not. In fact, Newton played a significant role in the development of chemistry, well ahead of his time, by advancing the corpuscular theory of matter and light, which didn’t deviate too far from the idea of atomism. He described it with his own inevitable religious slant as part of his great work on Optics in 1704:
“God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, of such sizes and figures, and with such other properties, and in such proportion to space, as most conduced to the end for which he formed them.”

Light was formed from these tiny corpuscles, or miniature specks of matter. Heavier objects were made from larger elements – still too small to see with the naked eye, but imparting on each object its properties. The corpuscular theory of light survived for some time, but was eventually superseded by the wave theory in the mid-19th century, to come back shortly afterwards, and we will meet it in a later chapter.

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As we have seen with the story of the invention of Chemistry and from previous chapters, the 19th century was a time of many great revolutions. Not just socio-political revolutions such as the on-going frisson in post-Napoleonic France, the American Civil War, and the Industrial revolution in Western Europe – it also bore witness to two highly significant scientific revolutions that we have seen, in Chemistry (from Lavoisier) and Biology (from Darwin).

Conventional wisdom, derived from the scientific theory of Aristotle, had stated that all materials were in some sense mutable – you could turn earth and water into a tree and a crop of apples, you could cut down the tree and compost the apples and turn them all back into earth and water. This was because they were all believed to share some remarkably simple fundamental building blocks, and that the properties of each substance were merely due to the differing proportions of the same four elements – earth, air, water and fire – of which all things were supposed to be constructed.

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54 Isaac Newton, *Opticks*, 1704

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Simple though this model might have been, and though Newton largely overturned the legacy of Aristotle in the 17th Century, we now know it to be largely correct, at least in a very vague sense. We know that all chemicals are really made from atoms of so-called chemical elements – the building blocks from which all the extraordinary variety of the chemical world can be derived. The mistake the alchemists made was not realising that many of the chemicals that they were trying to turn into each other were in fact elements themselves, like lead and gold – and they were therefore immutable and distinct. What they were attempting to accomplish was like, under the Aristotelian scheme, attempting to turn fire into water. Newton would have thought that laughable in just the same way we now see that his own efforts to turn lead into gold were also utterly futile.

But as all these discoveries were forming the bedrock of the subject of Chemistry, in biology the reverse was true – the conventional picture up until the work of Darwin was that all species were immutable and fundamentally different – that they possessed varying and distinct essences which made, say, a cat different from a dog or a squirrel different from a frog. But thanks to the discovery of evolutionary theory, we now know that, far from being completely distinct and immutable, all species have a common origin and all share the exact same genetic language within their cells. So the Chemical revolution broke life down into a small palette of discrete elementary building blocks, just as Darwin was busy showing us how living things inhabited a continuum of varied forms. The 19th Century was not just a time of enormous social upheaval, but it was also the period in which our comprehension of the natural world was turned upside-down.

Yet the 19th Century is not quite over yet. We have patiently followed the story of atomic physics until it now seems to be reaching its final page – with all evidence suggesting that the long quest to understand the physical world is finally coming to a close. But before we step out into the heady world of the twentieth century, we should pause to reflect on some of the extraordinary technological discoveries that this
surge in Scientific productivity brought with it. In the next chapter, we will look at perhaps the most disruptive technological achievements of the 19th Century, and see how they laid the foundation for the modern world.
Whispering Afar

“Plato is my friend — Aristotle is my friend — but my greatest friend is truth.”

Newton

Isaac Newton was a prolific letter writer, and quite a few of his written conversations survive to this day. Unsurprisingly, given what you now know about his abrasive personality, he wasn’t one to share joyous personal anecdotes about the trivialities of everyday life. As you might imagine therefore, a large fraction of his personal correspondence concerns explosive disagreements with his scientific rivals.

Newton was fond of conducting his arguments through the medium of wonderfully barbed letters, with a superficial veneer of politeness barely disguising a seething torrent of caustic abuse beneath. Newton and Leibnitz never actually met in person, which was probably a good thing. After all, when arguing by letter one has a certain amount of time to calm down before the response returns.

As in Newton’s time, and for almost all of human history, the speed of human communication depended only on the speed with which a human messenger could travel, either by foot or riding on the back of some accommodating animal. There were other techniques, of course. Messages could be sent by noise (shouting, screaming, singing, drumming) or visual cues (smoke signals, fire beacons) but those techniques were not suitable for transmitting complex information over long distances. The lengthy and expensive system of coastal beacons used in England in the late 16th Century certainly had the ability to send
a single warning ( “The Spanish Armada has been spotted!”) from the coast to central London in remarkably short time, but it was hardly suitable for carrying out a conversation. Or even, as might have been useful, conveying some idea as to the size and movements of the aforementioned enemy fleet.

The story of how humankind learned to communicate over long distances marks an extraordinarily important transition in the history of our talkative species. It’s certainly true that many of the gadgets we rely on today can trace their ancestry directly back to ground-breaking discoveries that took place in the late 19th century, spurred on by warfare and commercial competition but ultimately bringing human beings closer together than they had ever been before.

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It is so easy to forget, living as we do in an era of pervasive electronic communication, that only a few short generations separate us from an age when an entire government could fall on the other side of the globe without anyone in London or Paris finding out about it for weeks or months. Governing an empire was a highly decentralised task, hindered by the inability of any government to keep track of news and events taking place outside its immediate reach. Living in a time when we are able to place telephone calls to the moon, and we regularly receive photographs from space probes at the outer edges of the Solar System, the Earth seems so small that human society appears to spread seamlessly across the continents. But it was not always so.

Newton would have been familiar with many of the stories of the Roman Empire, of the rise and fall of that great civilisation and of the incessant tide of betrayal and assassination that corrupted it from Julius Caesar onwards. The pressing question that historians have continued to ask themselves throughout the ages is: Why exactly did the Roman Empire fail? What could possibly have allowed such a vast and
technologically superior superpower to perish at the hands of opportunist barbians?

The celebrated historian Edward Gibbon (1737 - 1794) in his remarkable work *The Decline and Fall of the Roman Empire* offers his own answer to that long-standing question: a combination of ineffectual and unpopular leadership; the impact of Christianisation (especially in its vicious and internally destructive conflict with the existing pagan religions, and its underlying pacifist tradition); a few poor military decisions, and the influx of barbarians from the north who assaulted a frontier that was simply too wide to control. Gibbon’s emphasis on the detrimental effect of religious conversion may not win much support nowadays, but whatever the reasons for the Roman Empire’s eventual dissolution, one problem that every large power before and since has had to grapple with is the fundamental limit imposed on the size of an empire by the nature of human communication.

The Roman Empire still ranks as one of the greatest ever human civilisations, and at its greatest it boasted a population of 80 million people in an area of 6.5 million square kilometres (more than two-thirds as large as the present-day United States). As the Empire had grown steadily over the centuries, it had incorporated increasingly diverse nationalities and geographies from North Africa, through Mesopotamia, Mediterranean Europe, and right up into what we would now call Southern Germany and Northern England. It had two major languages – Latin and Greek – and many local languages and dialects throughout its numerous territories.

In order to solve the problem of communicating across such a vast area, the Emperor Augustus (63 BCE – 14 CE) designed an extraordinary communications system known as the *Cursus Publicus*, which he used to pass messages around the entire length and breadth of the Empire.

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The system consisted of a comprehensive road network, with villas situated at regular intervals along the way in order to provide food and drink, a place to rest and fresh horses for the onward journey. Most of these ‘stages’ contained forty horses, together with all their staff and provisions. This was not a trivial expense - the emperor knew that the speed of communications could mean the difference between victory and defeat. Because of the expense and importance of the system, it was reserved for only the most important of customers.

The benefit of the *Cursus Publicus* was enormous. Using this method a parcel could travel as much as 100km per day, and could sustain that speed for long distances.\(^5^6\) A single rider could only travel rapidly for a day or two before his horse would collapse from exhaustion, but with a ready selection of fresh horses, food and drink at convenient locations along the route, such a speed could be maintained indefinitely.

The Roman Empire stretched several thousand kilometres at its greatest extent – London to Alexandria is a journey of 3,300km in a straight line by air, and much further once you take into account the indirect land route, the mountains in the way and the effects of weather and fatigue. So even with such an extensive system as the *Cursus Publicus*, it would still have taken two months or more for a message to travel this distance, though that is already far more rapid than any of the other options.

In today’s interconnected world it’s difficult to imagine being so disconnected from our fellow human beings. Perhaps at some point in the future, when humankind starts to voyage towards nearby stars, we will once again be faced with similar problems, but that won’t happen in my lifetime. Yet the Roman Empire was so large that, even if the Emperor died and messengers were immediately sent out in all directions, some parts of the Empire would never find out for two whole months. This is approximately the length of the reign of Emperor

\(^{56}\) A.M. Ramsey, The speed of the Roman Imperial Post. Journal of Roman Studies 15, 1925, 60-74
Didius Julianus in 193CE. So just as the first messenger was reaching his destination with the glorious news of a new Emperor, another was setting off from Rome with news of that same Emperor’s execution.

In the late 3rd century, the Emperor Diocletian decided to divide the empire in two, creating a co-emperor Maximian, whom he left in charge of the armies and the Western portion of the Roman territories. This Western Empire was initially based around the capital in Rome, eventually shifting to Milan and Ravenna as the boundaries reorganised after numerous conquests and defeats. In the East, the capital of Constantinople (originally Byzantium) soon became the richer of the two, and after the fall of Rome in 476CE, this Eastern capital carried on the torch as the sole remaining power, governing the remaining fragments of that once mighty civilisation. Despite brief bursts of conquest, it never permanently regained its original glory, and gradually shrank until the forces of the Ottoman Sultan Mehmed II finally conquered the city in the year 1453.

Wending our way forwards by a few centuries, we arrive at the mid-nineteenth century, in the year 1836. By this time, warfare was a great deal different to that known by the Roman empire, with muskets and rifles replacing swords and javelins, yet human beings were still going to war for the same old reasons as they had for the entire history of our bloodthirsty species. Now, however, there was a new battleground, in the new continent of North America, home to the United States of America which had been formed just 50 years previously. The United States were still at war with Mexico, its neighbour to the south, and this very year saw the famous Battle of the Alamo, when Mexican soldiers assaulted and overran the Alamo mission in San Antonio, Texas, slaughtering its defenders and continuing a period of unrest that culminated in the Mexican-American war of 1846-8.

At this time, Texas was part of Mexico, though continuing immigration from the North meant that Mexicans were now a minority and were rapidly being evicted from Texan soil. Mexico itself had only just
gained its independence from Spain in 1821, and it was fiercely defending its national borders against the separatist movements in Texas who had made clear their own intentions to secede from the Mexican government. Mexican troops assaulted the Alamo on 23rd February, finally capturing the entire complex on 6th March. Yet it was all in vain - during this period, on 2nd March 1836, Texas formally declared its independence from Mexico.

Though these battles were conducted in a wholly different continent, with very different weaponry and armour, speaking different languages and fighting for different leaders, yet one fundamental element had remained the same since the time of the Romans – news of battles, or indeed of any significant political event, would take weeks or even months to reach its intended recipient. President Andrew Jackson, in office at the time of the Alamo attack, was located in Washington, a journey of 2,600 kilometres. Nowadays that’s feasible in 24 hours by car, but on horseback (and without the Cursus Publicus available to the ancient Romans) it could easily have taken a month. By the time Jackson learned of the attack, it was already nearly April, and by the time a message could have made its way back from Washington to San Antonio, the Texan revolution was over, and the Mexican President Antonio López de Santa Anna, had been captured at the battle of San Jacinto on April 21st. Needless battles were fought on many occasions between forces who had not learned in time that they were no longer at war. It is difficult to grasp this concept in the 21st Century – no doubt even more difficult for the younger generations who grew up since birth with instantaneous electronic communications at their fingertips. The world must have felt truly vast.

Yet in this same year, 1836, the American inventor Samuel Morse (1791 – 1872) was already working on an invention that would revolutionise communication for all time. Just seven years later, in 1843, Morse had built the first telegraph system from Washington DC to Baltimore, a distance of 65 kilometres, able to transmit messages via a code system that he had derived and which today bears his name. When it was first
demonstrated to the US Congress in May 1844, Morse transmitted the message “What hath God wrought?” to highlight the staggering social changes that he knew he had unleashed. A message that would have taken a day to deliver on horseback could now be transmitted instantly. The line was soon extended to New York (roughly 360 km or 4 days’ ride on horseback).

In 1860, a new service called the Pony Express had just opened, which copied the ancient Roman *Cursus Publicus* and relied on fast riders relaying messages from California to Missouri on horseback in stages. It reduced the time for this arduous journey (2,600 kilometres, or roughly half way across the continent) to just ten days. Yet just the next year, in 1861, the first transcontinental telegraph was opened, allowing messages to travel the breadth of the continent instantaneously and rendering the Pony Express immediately obsolete. In merely 25 years since the Battle of the Alamo, it was now possible, during the American Civil War of 1861-5, to update President Abraham Lincoln with progress of his forces against those of the Confederacy almost in real time.

We could look at Morse Code as the first real method of long-range digital communication. The digital revolution in communications that began towards the end of the 20th Century contrasts with analogue techniques where the message itself is transmitted directly by some kind of variation in the underlying signal. So when we talk to each other face-to-face, our vocal chords vibrate, which causes air molecules to vibrate, and this pattern of vibrations is passed through the molecules in the air towards our recipients. On the receiving side, vibrating air molecules cause the listener’s ear drum to vibrate, which in turn vibrates the tiny bones of the inner ear where these movements are turned into varying electric pulses which are interpreted by the brain as variations in loudness and pitch, and decoded as speech.

Digital signals are different. In a digital signal, the message is *encoded* in a way that transforms the message into a series of simple pulses. In
Morse code, it takes much more time to beep out a series of dots and dashes than it would just to speak the words, but Morse code messages can be transmitted much more easily over long distances because all you really need to do to pass along a signal is to transmit either a pulse or no pulse. The sequence of dots and dashes are rigidly defined to be of a specific relative length, with pauses of varying sizes determining the gaps between letters and between words, yet the pulse strength can vary without changing the meaning of the signal at all. This means that it is possible to transmit a message across a communications link that is nowhere near powerful or clear enough to transmit the actual sound waves to which those dots and dashes might correspond.

For example, you could transmit Morse code using just a single lantern or flashlight – or using the fog horn on a boat. You could use a single tapping switch and a low-power transmitter to send a message thousands of kilometres and, even if the power dropped and the beeps became distorted or barely audible – all the receiver needs to do is to pick out the difference between a beep and not-a-beep – which is much easier than detecting the often subtle differences between specific sounds in spoken language.

In fact, even the drawbacks of Morse code – namely the fallibility of individual human operators – still vastly improved on the problems inherent in horse-based communication, merely because of the number of individuals involved. For each extra link in the chain, and for each person involved in transmitting message from A to B, there was extra cost, extra risk of mistakes being made, and perhaps even more importantly, additional points where human beings could maliciously interfere with the message itself.

Though there are numerous real-world examples of malicious intent made possible by early communications systems, perhaps the most famous comes from fiction, and concerns one of the main competitors of Morse’s telegraph technology, thousands of kilometres away across the Atlantic ocean.
Alexandre Dumas’s epic novel *The Count of Monte Cristo* is set in the first half of the 19th Century in Napoleonic France, at a time when passing messages around over long distances was of extremely high importance to a nation beset by war on all sides. A pivotal moment of the story comes towards the end where the hero, Edmond Dantès, having recently acquired a great deal of wealth - by means which I won’t explain so as to avoid spoiling the story more than absolutely necessary – bribes a telegraph operator to transmit a false message to Paris and thereby triggers a panic in the bond market which leads to financial misfortune for his sworn enemy.

The telegraph system Dantès uses is not that of Samuel Morse, but rather an earlier system directed by Napoleon himself (and later superceded by Morses’s system) called the *Système Chappe* after its inventors, Claude Chappe (1763 – 1805)\textsuperscript{57} and (at various times) his four brothers, Ignace, Pierre, René and Abraham. This remarkable invention was actually a semaphore system, relying on a network of communication stations fitted with roof mounted mechanical arms which were used to spell out messages over long distances. Each station was rather like a lighthouse, with a signal passing from one to the next in a line. The speed of transmission, and the accuracy of the message, relied considerably on the skill and alertness of the individual operators.

In fact Dumas’s story is not that far-fetched – in a famous case of the 1830s, two bankers were convicted of fraud by bribing a telegraph operator to transmit secret information about the movements in the Paris stock-market by introducing deliberate errors into his communications.

\textsuperscript{57} Chappe, incidentally, was born on Christmas day, just like Isaac Newton. Though, of course, he was born in the Gregorian calendar, not the Julian calendar, so they were not born exactly 121 years apart. Britain did not adopt the Gregorian calendar until 1752 – 110 years after Newton’s birth and 170 years after the same change was made in Chappe’s native France.
The Chappe system was a huge improvement on the existing horse-based system for sending messages. Chappe’s claim, made in a letter to the President of the National Assembly in 1792, was that he could transmit a message 100 miles in forty-five minutes, compared to at least a day by horse. With understandable excitement from the government, by August 1793 the money started rolling in and Chappe was able to put his plan into action across France. Within another year, the system was already transmitting news of the French army’s progress against the Prussians and Austrians. With the ascent of Napoleon Bonaparte in 1799, and his proclamation as Emperor in 1804, the development of a network of Chappe telegraph stations rapidly progressed, with lines stretching from Brussels, Lille, Strasbourg and Paris down to Milan and Turin. It proved to be another case of technology with clear military implications being given rather surprisingly large amounts of money by a government, only for its most dramatic uses to turn out to be entirely civilian.

Chappe’s life ended badly – he committed suicide in the winter of 1805 by throwing himself down a well in the garden of the Hotel de Villeroy in Paris. The cause of this rather brutal end is not known – though many blamed a deep depression that had been triggered at least partly by the increasing ferocity of attacks on his claims to have invented the technology that bore his name. Chappe’s early death, at the age of 41, meant that he was never to live to see his invention surpassed by the electric telegraph, and totally replaced by that American system within half a century. The last Chappe telegraph station closed in 1852, though a number were saved from demolition and have since been restored to working order as museums.

Though the telegraph undoubtedly revolutionised all western societies, that change was perhaps most keenly felt back in the United States where the technology had first been proposed. All of a sudden, a ragtag bunch of disparate states were able to become a coherent whole. Though the declaration of independence had taken place over eighty years earlier, it seems to me that the opening of the transcontinental
telegraph marked the true birth of the United States of America, and made possible the degree of coordination and information-sharing required to construct and maintain a stable country of that size. The distance from Los Angeles to New York is somewhere around 4,500 kilometres – approximately the same as the width of the Roman Empire at its greatest extent. And in 1861, the total land area of the United States minus the Confederacy was roughly the same as that of the Roman Empire under Trajan in 117CE (6-7 million km$^2$). I don’t think it’s pushing the evidence too far to say that the United States probably wouldn’t exist today as a single nation if it were not for the cohesion brought by instantaneous long-distance communications.

Yet the century was not yet out, and just a decade and a half after the opening of the transcontinental telegraph, in 1876, Scottish inventor Alexander Graham Bell (1847 - 1922) finally obtained the first ever patent for an “electric telephone” device. The telegraph pioneered by Samuel Morse had transmitted messages by the familiar code of dashes and dots that bears his name. Yet Bell’s device went one step further – transmitting the actual sound of human voice instantaneously over long distances.

Bell had always been fascinated with the science behind the transmission of sound using electricity, and his academic work supported this passion, building on the discoveries of many other prominent scientists, including Thomas Edison, to build his first prototype. Bell chose rather less ominous first words to speak through his device to his colleague Thomas A Watson: “Mr Watson, come here, I want to see you!”. Hardly the stuff of legends, but he may have had other things on his mind.

The telephone system didn’t expand quite as quickly as the telegraph had done – after all, there were more substantial technical problems to solve to ensure clear reproduction of sound, and the existence of the telegraph had taken the shine off the incentive to deploy a new system so soon – but on 25$^{th}$ January, 1915, as war waged in Europe, Bell and
Watson conducted a second landmark call by telephone, this time between New York and San Francisco (4,600 kilometres, or nearly seven weeks by horse).

The only drawback of Bell’s invention, of course, was the requirement to lay thousands of kilometres of wire across the continent (and in similar systems across Europe and the developed world). This not only took time, but cost a great deal of money, and was vulnerable to vandalism, theft and, of course, enemy attack in times of war. Laying a telegraph line across hostile terrain was not possible, which rather limited the uses of this new technology. A third breakthrough was required to get round this problem, and it wasn’t long before that, too arrived on the scene. Yet for this one, we must return to Europe, in particular the German Federation, as it was then known.

The years 1886-8 saw, in a very real sense, the invention of the science of radio communication through the pioneering work of Heinrich Hertz (1857 – 1894), who was a professor at the University of Karlsruhe in modern-day south-west Germany. Hertz’s pivotal experiment involved generating electromagnetic waves by creating electric fields inside coils of wire, and he demonstrated that these waves could indeed propagate through space for some distance, with certain predictable characteristics. Using the measurements he took, Hertz was able to measure the speed of these waves, and showed that it was equal to the speed of light.

The fact that light has a finite speed seems even today like a fantastic claim. Thinking of light as a “thing” is a rather counter-intuitive concept, and it certainly hadn’t been thought of in that way for much of human history. The Ancient Greeks, of course, were first on the scene, beginning with the works of Empedocles in the 5th Century BCE, who suggested that we might see by means of light travelling from our eyes and towards the object, as if from a lantern. It’s the wrong way round, of course, but at least he was trying.
Empedocles ended his life, according to legend, by jumping into the fiery heart of Mount Etna in Sicily. It’s possible that he was testing his theory that human souls are reincarnated after death until they reach the pinnacle of human knowledge and perfection, at which point their souls are freed from the cycle of reincarnation and are able to return to the blessed life whence they came. It’s also possible he was mad. Empedocles was also the source for the “four elements” concept in natural philosophy, which was taken and developed by Aristotle. However, Aristotle didn’t have much time for his predecessor’s ideas on vision, so discarded them in favour of something far more abstract.

There was no dominant theory concerning human vision until the 11th Century, when Islamic philosophers started to consider the possibility that we see because something enters the eye from outside, rather than exiting the eye from within. It wasn’t until Newton’s lifetime, in fact, around his 33rd birthday in 1675, that the first measurement of the speed of light was performed by the Danish Astronomers Ole Christensen Rømer (1644 – 1710) and Christiaan Huygens (1629 – 1695) and the French/Italian astronomer Giovanni Domenico Cassini (1625 - 1712), using measurements of the satellites of Jupiter.

Rømer’s method was ingenious, though he didn’t actually plan to measure the speed of light at all. His experiments were designed to investigate the strange behaviour that he had noticed in the moons of Jupiter. The time it took for those moons to orbit their parent planet had been known accurately for some time, so in theory it should have been easy to predict exactly when the moons would pass behind Jupiter, out of sight of the sun. However, Rømer discovered that the exact timing of these eclipses wasn’t as constant as everyone expected, because the Earth and Jupiter were both orbiting the Sun, and hence over time they moved closer together or further away from each other. The obvious conclusion was that eclipses appeared to happen later when Earth was further away from Jupiter, because light took longer to travel the extra distance. If the two planets were closer together then the eclipses would appear to happen earlier than expected. From there, it just required a bit
of careful measurement and some geometry to obtain a value for the speed of light that was only about 25% away from the precise value we use today.

So thanks to the pioneering work carried out towards the end of the 17\textsuperscript{th} Century, the speed of light was rather accurately known. In fact, by the time Hertz carried out his experiments on radio waves, the exact value had been measured far more precisely, thanks to the work of the French physicist Léon Foucault (1819 – 1868), who got the measurement to within one percent of the true value using a cunning experiment based mainly around rotating mirrors.

The experiment is actually rather simple: Take a high-quality mirror spinning rapidly about a vertical axis. Now, shine some light at that mirror from a nearby source. Next, position a second, stationary, mirror some distance away. The further the better, though you’re limited by how well focussed your beam of light is. In the time it takes the light to bounce off your rotating mirror, travel to the stationary mirror, and bounce back to the rotating mirror, the rotating mirror will have spun a very small angle, so when the light bounces off it again, it will travel in a slightly different direction.

The trick, then, is to measure the angle at which the beam is reflected and calculating that angle as the fraction of the full circle. Then, given the time it takes your rotating mirror to make one full rotation, you know how long it took the light to travel from the rotating mirror, to the stationary mirror and back. And, given the distance between the mirrors, you can work out how fast the light must have been travelling. This experiment is simple enough to conduct in a high-school science class – and it makes a fantastic demonstration.
Hertz knew that electromagnetic waves travelled at the speed of light because they were caused by the same underlying physics. This much had been predicted by the work of James Clerk Maxwell, though Hertz was the first to demonstrate that Maxwell’s equations actually matched reality perfectly. Having said that, in a fine example of completely missing the point, Hertz didn’t seem to realise how profound this new knowledge might become. When asked what his discovery meant, he replied “It's of no use whatsoever”.

Hertz never lived long enough to discover how wrong he was, dying at the tragically young age of 36 from a neurological condition over which there is still some debate. Yet his widow lived to see his memory honoured not only by the naming of the internationally-recognised unit of frequency the “Hertz” in 1930, but also because, the very year after Heinrich died, a young Italian-Irish inventor called Guglielmo Marconi (1874 – 1937) began to demonstrate how to transmit information using these newly-tamed radio waves, by subtly modifying them in relation to the signal that he wanted to send. In 1894 Marconi managed to transmit signals for a few metres. By the next year he could reach two or three

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59 One Hertz or 1Hz is one cycle per second. So the “MegaHertz (MHz)” you see on radio stations are millions of cycles per second.
kilometres, and then in 1897 he famously transmitted a message six kilometres across the Bristol Channel (“Are you ready?” Again, hardly Shakespeare.)

Yet the Italian’s hard work continued to pay dividends. In 1899, Marconi sent signals across the English Channel between southern England and France, and then just two years after that, in 1901, merely seven years after the first ever radio transmissions, he transmitted a signal across the Atlantic Ocean between Cornwall and Newfoundland, a distance of 3,426 kilometres (or five weeks by seahorse).

Marconi won the Nobel Prize for Physics in 1909, and was consequently granted many of Italy’s highest honours, eventually gaining a Peerage in 1926. Elevated by his fame, he fell in with the Italian fascist party in the years before the Second World War, and went somewhat off the rails. Benito Mussolini was the Best Man at his wedding. One can only imagine the speeches…

Marconi died before he could see the terrible effects wrought by European fascism, though it could certainly be said that the association does him no favours in the annals of history. Yet one cannot deny the enormous contributions his pioneering work delivered, not least of which within the trenches of the first World War where it was now possible for the commanding officers to communicate with the front line without laying wires throughout the battlefields. One might note that this also marks the period in which a few of the senior commanding officers started to position themselves several miles away from the fighting because, well, now they could.

I find it strange to reflect that the story of long-range communication owes so much to figures like Marconi, with his fascist sympathies, and Samuel Morse, who was pro-slavery and strongly anti-immigration. Ironically, this ability to communicate with other human beings over long distances has perhaps brought the world closer together than any other invention in human history. The first public radio broadcasts in
1920, rapidly gaining momentum in the years afterwards, ushered in an age where people of all creeds and colours could listen to the same voices, the same music, and the same stories at the same time, regardless of whether they were black or white, rich or poor, highly educated or illiterate. Radio put people in Britain in touch instantly with those in America, or Russia or North Africa – worlds apart. Countries so seemingly distant that they would previously have taken weeks or months to reach, were now joined together as if they were neighbours.

Of course, long-range communication also had a dark side – the power that enabled individuals to share information over long distances also allowed governments to control and direct the minds of an entire country, as demonstrated by the propaganda campaigns run by Joseph Goebbels and other fascist leaders throughout the 1930s and until the end of the Second World War.

But long-range communication offered great benefits which outweighed the bad. It fostered collaboration, learning and sharing of culture; the foundation of global supra-National unions such as the European Union, the Arab League or the Association of South East Asian Nations, not to mention NATO, the United Nations, and the various charities and non-profit organisations working to bridge gaps between the richest and poorest nations on Earth today. All of these are only possible because people from diverse countries, many thousands of kilometres apart, are able to communicate directly and instantly with each other to share one coordinated vision.

Unlike many of the profound technological advances that we have seen so far, these new communications technologies all exploded onto the market rather quickly. It was just 57 years between Samuel Morse’s first telegraph message and Marconi sending radio signals across the Atlantic. Such extraordinary changes, taking place well within a single human lifetime, understandably revolutionised the lives of everyday folk throughout the most advanced nations on Earth. The rapid
modernisation of the Industrial Revolution was already causing widespread social upheaval, wrenching apart communities that had stood for Centuries, but now it seemed like technology was bringing people back together again.

I find it hard to imagine that Newton would have much relished the invention of the telephone and radio – he valued his own privacy, and very much disliked being bothered by people whom he regarded as his intellectual inferiors pestering him when he was trying to think through the mysteries of the Universe. What he would have made of telesales and phone surveys one can only imagine. Newton was firmly a letter writer – this gave him the opportunity to put his thoughts in order as forcefully as possible, and also allowed him to avoid direct contact wherever possible.

Though I have been fairly harsh about Newton’s characteristic rudeness, it must be said in his defence that he was not the only one to fill his letters with vitriol. The Astronomer Royal, John Flamsteed, wrote to his publisher in 1706 about his experience dealing with Isaac Newton:

“I always found him insidious, ambitious and excessively covetous of praise, and impatient of contradiction.”

Probably not an unfair comment, I suspect, given what we know of Newton’s character, though it was rare for anyone of the time to vent their dislike of a colleague with such passion and bluntness.

Yet not all Newton’s communications were antagonistic. In a meeting of minds that one might, in retrospect, assume comical, Newton also entered into correspondence with the famous diarist and social figure, Samuel Pepys. Though both were hard-working, wealthy and respected public figures, that’s about as far as the similarities went. Pepys, in dramatic contrast to Newton, was a sociable man, fond of entertaining, enamoured of the arts and an able musician, not to mention something
of a serial adulterer. Newton, as we have seen, was not particularly fond of people, often spending a considerably effort to avoid speaking to them, and he never had any serious romantic relationship of any kind, as far as we can tell. Yet, despite their different tempers, the two men knew each other well through the Royal Society, of which Pepys was the President 17 years before Newton.

In September 1693, Newton wrote to Pepys a most alarming letter, in which he seems to be claiming that he is suffering from some kind of mental illness.

“I am extremely troubled at the embroilment I am in, and have neither ate nor slept well this twelve month, nor have my former consistency of mind. I never designed to get anything by your interest, nor by King James's favour, but am now sensible that I must withdraw from your acquaintance, and see neither you nor the rest of my friends any more,...”

Perhaps out of worry for Newton’s health and wanting to give him a puzzle worthy of such a mind, or maybe merely to satisfy his own curiosity, in November 1693 Pepys wrote again, seeking Newton’s advice on a mathematical bet that he was intending to make. The problem was simple to state, though substantially harder to solve. Pepys wondered what was more likely: Throwing at least one six with six dice, two sixes with 12 dice or three sixes with 18 dice. He suspected the latter, and wanted Newton to prove it. Newton, on the contrary, proved that it was the former, though the intuitive explanation he gave to Pepys was, oddly for Newton, completely wrong. Newton attempted to argue that, in order to get three sixes on 18 dice, it was necessary to roll one six from six dice, and do this three times. Which is, of course, false (you could roll three sixes in the first six dice, and none in the rest, for example).

60 Isaac Newton, Letter to Samuel Pepys dated September 13, 1693.
It might be the most embarrassing mathematical mistake Newton ever made – though fortunately the correct answer was obtained anyway (he calculated it more rigorously too, and this time got the method right.) It wasn’t the only mistake he ever made – there were errors in his first draft of *Principia Mathematica* – but one might consider them somewhat more forgivable given the complex nature of the work.

We have no evidence that Newton ever uncovered the mistake in his letter to Pepys, and it seems likely that this intuitive explanation was just an after-thought that he added to the end of the letter as it came to him in a moment of mistaken clarity. It might be a fitting point to end this chapter by demonstrating that, despite his extraordinary genius, his savagely argumentative temper and his increasing isolation from society, Isaac Newton was, after all, human. And perhaps the most revealing letters we ever see of Newton are taken from the uncharacteristically gentle communications he shared with his beloved Niece, Catherine Barton.

On 5th August 1700, Newton wrote a short letter to Catherine⁶¹, who had been taken ill with a fever. “*Dear Niece...*” he begins, before offering his best wishes for her swift recovery. “*I intend to send you some wine by the next carrier, which I beg the favour of Mr. Gyre and his lady to accept.*” He urges her to stay in contact, offers some medical advice “*Perhaps warm milk from the cow may help...*”.

And then signs off with an uncharacteristic tenderness that perhaps gives us a glimpse at the human being beneath the academic robes.

“*I am your very loving uncle, Is. Newton.*”

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⁶¹ See [http://www.newtonproject.sussex.ac.uk/](http://www.newtonproject.sussex.ac.uk/) for a complete repository of Newton’s correspondence.

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An Unfamiliar World

“Truth is ever to be found in simplicity, and not in the multiplicity and confusion of things.”

Newton

For most of the history of our species, we human beings have relied on our intuition to understand the Universe. Our minds are highly tuned to make sense of our surroundings, to interpret the information coming from our senses and to build up a model of the world that allows us to avoid dangers and exploit opportunities. By the end of the 19th Century there was great optimism that the scientific endeavour was almost at an end; that we were on the cusp of compiling a full and complete explanation for all of nature’s secrets. All that remained, it was believed, were just a few remaining pieces of the puzzle.

Yet as the clock ticked over, and 1900 began, distant storm clouds were appearing on the academic horizon, punctuating the gentle haze of Victorian complacency. A series of famous experiments were suggesting that this whole cosy situation was probably not going to last much longer. As the 20th Century dawned, the scientific landscape was showing the first few tremors of a profound and terrifying tectonic shift that would bury the old way of thinking familiar to Newton and his contemporaries once and for all.

In this chapter I will investigate one of the most disturbing and troublesome periods of science, where we went from knowing everything to knowing nothing in the space of a decade. And yet, from the chaos of the early twentieth century, emerged two new scientific
theories that had the potential to provide us with previously undreamt of levels of power and understanding.

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As the curtains began to fall on the nineteenth century, it looked as though the end of physics was drawing nigh. The past hundred years had seen unprecedented levels of discovery across all the sciences; humanity had witnessed countless social changes and a large-scale upheaval of all western society; the hard work of scientists across the globe had brought the discovery of new and powerful principles that enabled instantaneous communication, portable power generation and control over the very forces of nature; recent advances in medicine would soon see the most terrifying diseases of history completely eradicated from the world. Even the word “science” had been invented to describe the extraordinary process that had brought so many invaluable wonders in such a short time.

The revolution that Newton had begun was truly nearing its spectacular final act, with just a few loose ends remaining to be tied up before we could declare ‘mission accomplished’. In 1894, the distinguished physicist Albert Michelson (1852 - 1931) gave a speech at the dedication of the newly-built Ryerson Physics Laboratory at the University of Chicago. In it, he gave his own opinion of the current state of physics as the great Century drew to a close.

“The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote…. Our future discoveries must be looked for in the sixth place of decimals.”

Michelson later received the Nobel Prize in Physics – the first ever American to do so – primarily for his work in studying the spectrum of
light. Ironically, the main achievement for which he is known today is a famous experiment that actually began to cause some inquisitive scientists to question the old way of thinking that Michelson had so confidently claimed would last forever. It had always been assumed that light, just like sound, needed some kind of medium in which to propagate. It made sense – after all, if light is a wave then it has to be a wave of something. Together with his colleague Edward Morley (1838 - 1923) Michelson set out in 1887 to demonstrate that light did indeed travel through a hypothetical medium known as the ether – the existence of which had been assumed for decades. However, the experiment showed precisely the opposite – the ether did not exist and so light clearly did not require a medium through which to travel at all.

This discovery caused some considerable confusion amongst physicists. The ether was such a central part of the theories at the time that many great minds expended a great deal of effort trying to think of ways in which the Michelson-Morley experiment might have been wrong, but nobody succeeded. Michelson and Morley had cleverly showed that the time taken for light to travel a fixed distance does not depend on its direction of travel relative to the motion of the Earth. If there were an invisible substance spread across all of space, and if that substance were involved in transporting light, then you might imagine that it would be harder for light to travel in the same direction as the movement of the Earth rather than perpendicular to it. Rather like trying to throw a ball into a headwind. Yet it turned out that this assumption was false.

Michelson believed that his life’s work was going to be spent refining the last few letters of the great book of physics, rather than writing totally new chapters. Yet he could barely have known that this discovery – which surprised him as much as it did the rest of the scientific community – would sow some of the seeds that would lead to arguably the most extraordinary scientific revolution of all time.

So Michelson’s work caused some confusion for astronomers, yet at the other end of the scale work was progressing in understanding of the
structure of the atom. Now I appreciate the irony here – ‘atom’, as I have already said, comes from the Greek for ‘uncuttable’, so to propose that an atom has internal structure surely implies that it could be further subdivided. Perhaps the best way to duck this mild linguistic faux-pas is to think of what we mean by ‘uncuttable’. In reality, the atom is the smallest unit that could be considered to possess the qualities of the element that it represents. A Carbon atom is the smallest thing that is “Carbon”; an Oxygen atom is the smallest thing that is “Oxygen”, and so-on. So when we talk about dividing an atom, we are really talking about diving beneath the scale at which chemical elements can be distinguished from each other, and pulling apart those constituents of all atoms that grant the properties that make Carbon behave like Carbon and not like Oxygen, and so on. Perhaps you could think of it like dividing a country’s population down into its individual human beings. Sure, you could continue to divide those human beings into bones and flesh and internal organs and so on, but that’s a completely different type of division that tells us far less about the behaviour of those same people and the properties of the country to which they belong.

So by the end of the 19th century, scientists were keen to look inside the atom and discover what lay within. The concepts of magnetism and electricity were now well understood and speculation was mounting over the existence of a single unit of electric charge that could be held responsible for some of these powerful effects. The British physicist, Joseph John Thomson (1856 – 1940) has been most closely linked to the discovery of this elementary particle, which we now know by the name “electron”. In reality, though his experiments were the most definitive, various laboratories across Europe had made significant progress in the late 19th century, starting with the discovery of so-called “cathode rays” in the 1870s, primarily by work done in Germany and Britain. Those who remember old-style CRT (Cathode Ray Tube) televisions will be familiar with the phrase. A cathode ray was an energetic stream of electrons emitted by the negative electrode (cathode) of an electric circuit enclosed in a vacuum.
Thomson’s work not only isolated and verified the existence of individual particles in the cathode rays, but he also measured their charge and mass. This allowed him to deduce that these ‘electrons’ were at least 1000 times less massive than a Hydrogen atom, and that they possessed a tiny negative charge. Given that electrons could be created from matter, it seemed likely that electrons were found within the atoms from which that matter was constructed.

It was already well known that entire atoms are electrically neutral – they have no net positive or negative charge. So the fact that atoms contained electrons meant that they also had to contain an equal quantity of positive charge to cancel them out exactly. Hence, in 1904 Thomson suggested a model for how the atom might be structured internally, with a spherical cloud of positive charge containing individual electrons dotted randomly inside. The model was known as the “Plum Pudding” model, after the traditional English dessert which contains individual pieces of fruit inside a (generally approximately spherical) ball of sponge cake. Smothered in custard. I think the custard might not be relevant for the analogy, but it’s definitely vital for the dessert.

No matter how delicious it sounds, the plum pudding model was unfortunately short-lived. Just five years after it was proposed, an experiment carried out by the New Zealand-born British physicist, Ernest Rutherford (1871 – 1937), comprehensively disproved this simplistic view. Rutherford, together with his young colleagues Hans Geiger (1882 – 1945) and Ernest Marsden (1889 – 1970) set up an apparatus where a thin piece of gold foil was showered with a certain type of particles from a radioactive source. These particles – called “alpha particles” – are highly energetic, positively charged and fairly easily absorbed by thin layers of metallic shielding. So when shining a source of these alpha particles at a thin gold film, the expectation was that most of them would pass through un-deflected, but maybe a few would be absorbed. If Thomson’s model was correct, then the positive charge of the gold atoms would be spread out over a large volume, and the
negative charges would also be randomly placed, so any repulsion or attraction would be smoothed out and, as there was an equal amount of each, it should neatly cancel. Think of it like firing projectiles through a thin curtain of water in a waterfall – though the water contains lots of mass, it is spread out evenly over a large area, so a sufficiently fast bullet would pass straight through.

However, what Geiger and Marsden observed was that, though most of the alpha particles passed straight through the foil as expected, a small number of the alpha particles were not only deflected on passing through the foil, but were actually deflected by a very large angle. It was as if you unloaded an automatic rifle into thin curtain of water and a handful of the bullets bounced back right at you! This could not be explained unless there were concentrated points inside the gold foil where the positive charge greatly outbalanced the negative charge, and repelled the incoming alpha particles very strongly. This was not at all what Thomson’s model predicted and two years later, in 1911, Rutherford proposed a new model to supplant the Plum Pudding based on the results of this novel experiment.

Rutherford’s model suggested that the positive charge was concentrated at a single point in the centre of each atom. For atoms to remain neutral, they still had the same quantity of negative and positive charge, and the negative charge was still distributed across the atom, but the positive charge was all at the centre. This central concentration became known as the nucleus, and outside that the atom was mostly empty space. If that were not the case, then the majority of alpha particles would not have passed unscathed through the gold foil, as Rutherford discovered.

In fact, Rutherford could do better than that. Based on the precise results of the Geiger-Marsden experiment, he calculated that the nucleus was only a tiny fraction of the size of the atom. In fact, his findings showed that it occupied less than one sixty-billionth of the total volume of the atom. Modern scientific measurements have actually reduced this tiny number by more than another factor of 100, leaving us
with the unsettlingly counterintuitive realisation that almost all of matter is, in fact, empty space. It doesn’t seem that way to us on our much larger scale, of course, but in a certain sense it’s true. If you imagine an atom expanded to the size of a football stadium, the nucleus would be approximately the size of a pea at the centre. This is a chapter full of counterintuitive discoveries, as I warned you at the offset. There are plenty more to come.

Rutherford’s model was another great leap forward, but such was the pace of discovery at this time that it was only two short years before even this brand new image was completely overhauled. Physics had truly entered its golden age.

J. J. Thomson was awarded the Nobel Prize for Physics in 1906, and Albert Michelson followed him the next year. Physicists had a new model of atomic structure that agreed with almost all the observational evidence available at the time. There may have been one or two small loose ends left over, but it was felt that these remaining problems were minor and should be fairly straightforward to tie together somehow.

Yet as great minds tugged at those loose ends, they began to unravel, and not only did they pull apart some of the existing theories that had seemed so certain – but they also drew attention to a few quirks of nature that showed that the whole scientific picture was nowhere near as simple as Rutherford and Thomson might have hoped.

In fact, the revolution had already begun. Shortly before Michelson and Thomson travelled to Stockholm to receive their recognition from the Nobel committee, the scientific community was rocked by a salvo of academic papers that seemed to undermine everything we knew about matter. The year was 1905, and the author was, of all people, a hitherto unknown Swiss patent clerk.

The transition between these two worlds can never be ascribed solely to one single individual, but in this case, two extraordinary individuals do
stand out above the rest. The first is that same Swiss patent clerk, Albert Einstein (1879 - 1955), whose theories of Special and General relativity, along with his early work on the foundations of quantum mechanics, made him something of a scientific superstar – perhaps the first in history – and gave us the one scientific equation that is recognised more than perhaps any other before or since. The second is Max Planck (1858 - 1947), a German physicist whose discoveries paved the way for Einstein’s great breakthrough.

Max (Karl Ernst Ludwig) Planck was a German theoretical physicist from a family of career academics. His life was a tragic one, living as he did through humiliating and devastating defeats in the two great wars of the 20th century, losing his first wife to tuberculosis, and watching four of his five children die before him, three of them in their thirties, two of whom died in childbirth bearing children by the same man. Yet Planck fought stoically through these dark times, utterly focussed on understanding the secrets of the Universe at its smallest scales – the world of the atom.

The most famous mystery that Planck worked to decipher was the so-called “Black Body Radiation” law. It deals with the way that hot objects radiate energy, and how the characteristics of that process are affected by the object’s temperature.

Now a hot object gives off energy by radiation – this is why a red hot barbecue feels hot even when you are standing a distance away from it, and it’s also how we receive heat from the sun across 150 million kilometres of intervening space. And by ‘radiation’, I’m talking about electromagnetic radiation – light – the same process that we’ve been talking about since Newton’s *Optics*. Some of that light is emitted at wavelengths we can see, but much of it is not. For example, as we go beyond the reddest end of the visible spectrum, we begin to move into the area of the Infrared. Our eyes can’t see this kind of light, but our

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62 And, unsurprisingly, understood by almost nobody.
bodies can detect it as heat. It is at these longer wavelengths that most objects in the world emit the majority of their energy. Some predators can see partly in the Infrared, which means that they are able to see warm-blooded creatures at night even when the Sun’s rays have long since fallen below the horizon – to them the natural world is dotted with faintly glowing sources of light.

The precise manner in which hot objects radiate heat depends largely on their temperature. The hotter an object, the more energy it emits in total, but there is another important difference. If you have ever watched a metal object heated in the heart of a furnace, you will no doubt have noticed that as it heated up its colour changed, from black, through reds and oranges to yellows as the temperature approached melting point. The hotter the object emitting radiation, the bluer the light given off – that is, the higher the average frequency of that radiation.

Let’s take a closer look at that last paragraph. The higher the energy of radiation, the higher its frequency. Frequency basically means the number of times a wave vibrates per second. So that sort-of makes sense – if you imagine adding energy to something it tends to move faster, so you might imagine that light with higher energy vibrates more rapidly. Now imagine a light wave entering your eye, vibrating at a certain frequency, as uncountable billions do every second of every day of your life. You can see that situation in the diagram below. Note that the wave has a certain wavelength – the distance between any peak and the next peak. As light enters the eye at a fixed speed – the speed of light – we know how many of these peaks will enter the eye per second. That number is the frequency. If the wavelength doubles then, given that the speed stays the same, the number of peaks entering the eye will halve (because each peak is twice as far apart from its neighbours as it was before), and so the frequency will be half what it was before.
So far so good – because light travels at a fixed speed, a short wavelength means a high frequency (more peaks per second), and a long wavelength means a low frequency (fewer peaks per second). All that remains is to translate that difference to \textit{colour}, because the colour of light basically means its wavelength.\footnote{Well, given that frequency and wavelength are so closely related, if you know one then you know the other. So you can think of ‘colour’ as a feature caused by the wavelength or the frequency of the light.} Longer wavelength light is redder, and shorter wavelength light is bluer – that’s just a trick that our brains do so that we can understand the difference between long wavelength and short wavelength light. So our Sun appears yellow, whereas a cooler star might appear red (red being a longer wavelength of light compared to yellow) and a hotter one might appear blue (a shorter wavelength).

However, it had been known for some time that the exact picture was a little more complicated than this, largely based on Newton’s discovery that white light contained an entire spectrum of colours. If we measure the light from our Sun, we see that it doesn’t emit light in one single colour, but rather it emits light in a wide range of colours, with a distinct peak at a wavelength around 500 nanometres, or $1/2000^{\text{th}}$ of a millimetre. Though the Sun looks yellow to us, its peak energy output is
actually in the green part of the spectrum. As you look at wavelengths of light longer or shorter than this peak value, the amount of energy you measure drops off rapidly. The shape of this profile was known to some extent from experimentation, but at the end of the 19th Century, nobody could explain accurately why it took the exact shape it does.

Fig. 6: The “Black Body” spectrum of three objects. The coolest one (the red curve) emits most of its light at lower energies (redder light) than the warm (green) and hot (blue) objects. You can see that by looking at the colour at which each curve peaks.

Ordinary every-day objects actually give off a very messy spectrum of light because of imperfections, and the effect of the chemistry of the object. A *Black Body* is a theoretical object which acts like a perfect emitter (or absorber) and hence absorbs everything that falls on it, and emits with a pure, smooth, untainted spectrum of light, without the messy perturbations that you get from experimental errors. Black bodies were used throughout the 19th Century (and, indeed, today) as a simple case study to test whether the theoretical, mathematical laws of physics were able to predict real-world phenomena. In practice, of course,
perfect black bodies don’t really exist, but many things (some stars, for example) are actually remarkably close, and the distinct ways in which they differ are extremely instructive.

Let’s return to the story. The exact problem that Max Planck had been working on was first proposed by another German physicist of the mid-19th Century named Gustav Kirchoff (1824 – 1887), to whom the phrase “black body” owes its origin. Kirchoff postulated (and at this point it really was little more than an educated guess) that black bodies give off light in a continuous spectrum, and that the amount of power they give off at any wavelength is only related to that wavelength and the temperature of the body – nothing else comes into the equation. Kirchoff’s Law was widely accepted by Scientists despite its one major flaw – namely that nobody yet knew what the form of that relationship should actually be. They knew that hotter bodies were “bluer”, colder objects were “redder”, and that the relationship was smooth and continuous. But exactly how this profile varied, and why it varied in that way, were both completely unknown.

This question occupied the mind of Max Planck for six years of his life, as he tried to find a solution that would answer this question based on a solid theoretical foundation. Whatever he tried, Planck rapidly came up against the same problems that his colleagues around the world had also met, and his models proved unworkable.

Besides Planck, the most famous attempt to model black body radiation was due to the British physicists John William Strutt, 3rd Baron Rayleigh (1842 - 1919) and Sir James Hopwood Jeans (1877 – 1946). Both were prolific physicists, with a great many achievements to their names in many diverse fields. But most importantly, at least for our present story, they together derived a mathematical relationship between the amount of radiation given off by a body at a given wavelength, and the body’s temperature. It was a direct solution to Kirchoff’s problem, but it went badly wrong towards the short-wavelength end of the spectrum.
The Rayleigh-Jeans law, as it became known, predicted that the amount of energy a body emits at a given temperature and wavelength grew in proportion to the temperature, but fell off far more rapidly as the wavelength increased\(^{64}\). In other words, if you double the temperature of an object then, all things being equal, the strength of the light emitted also doubles. But if you increase the wavelength of light that you’re measuring by a factor of two, then the Rayleigh-Jeans law said that the intensity of radiation you measure should drop by a factor of sixteen.

You probably don’t see the problem yet – and indeed the problem doesn’t really present itself until you start asking the question: “what happens when, instead of doubling the wavelength, you start halving it, and look at shorter and shorter wavelengths?” Well, if you halve the wavelength, then the quantity of radiation goes up by a factor of 16 instead of down. And if you halve it again, it goes up by another factor of sixteen. And if you halve it again… you get the picture. In fact, as the wavelength you measure gets shorter and shorter – towards the ultraviolet end of the spectrum – the amount of energy radiated at each frequency gets bigger and bigger in such a way that, if you sum up all the contributions from all wavelengths, the total should be infinitely large.

This, as you can imagine, is a problem, and it was named the ultraviolet catastrophe.

The nature of this problem very much confused Max Planck, and all others who attempted to solve it. Whatever they did, they were unable to come up with a physically realistic model for black body radiation that fitted the all existing observations but did not blow up horrendously at low wavelengths. It was in 1900, just as the new century was getting underway and at roughly the same time that Lord Rayleigh was deriving his own law, that Planck decided to try a totally new mathematical model to see how it would work. This new attempt was based partly on the form of the law derived by Rayleigh, and also on a

\(^{64}\) The intensity fell off to the fourth power, in fact.
different law derived by the German physicist Wilhelm Wien (1864 - 1928). Wien’s version of the law matched very well at short wavelengths but very badly at longer wavelengths. Rayleigh’s version was exactly the opposite – it matched very well at long wavelengths, but blew up at short wavelengths. Planck’s idea was to sort-of plug the two laws together and fudge the join in the middle so that the resulting behaviour would look rather like each of the laws in the domains in which they were accurate, but completely different in-between.

Even though it was little more than an educated guess, Planck’s formula turned out to fit the data extremely well right across the spectrum. This was confirmed shortly afterwards through experiments, ensuring Planck his place in the annals of history. But the most important aspect of this remarkable formula went largely unnoticed at the time. Even Planck himself failed to spot the remarkable discovery that he had inadvertently made, which would soon overturn the very foundation of physics.

You see, there was one little assumption that Planck had rolled into his work so that the maths would work out as he required. It was a simple idea, based on the controversial results coming from the field of Statistical Mechanics, largely due to the Austrian physicist Ludwig Boltzmann (1844 - 1906). Statistical mechanics provided a framework for understanding extraordinarily complex energetic processes amongst huge numbers of particles by making a few simplifying assumptions to make the maths a bit more tractable. In this case, Boltzmann’s work assumed that the possible energy levels of light emitted by the black body could only take certain fixed values, instead of varying continuously. It’s like playing chess – the pieces can only move from the middle of one square to another, they can’t take any arbitrary position on the board. This simplification makes chess playable as a game, even though it makes it less realistic as a depiction of actual warfare. Planck did the same with his maths to work out his radiation law. As far as he was concerned, this was merely a simple trick to make the maths easier, and it just happened to come up with the right answer.
he never actually considered that it might imply something important about reality.

In fact, instigating a scientific revolution was probably about as far from Planck’s mind as possible. When he was starting out on his studies in physics in 1878, he was advised against the career move by his physics professor Philipp von Jolly, who agreed with the sentiment of Michelson we encountered earlier, that the discipline was almost complete, with just a few holes left to fill in. Planck would later write that

“[von Jolly] portrayed to me physics as a highly developed, almost fully matured science... Possibly in one or another nook there would perhaps be a dust particle or a small bubble to be examined and classified, but the system as a whole stood there fairly secured, and theoretical physics approached visibly that degree of perfection which, for example, geometry has had already for centuries.”

Planck himself, partly without realising it, had just proved Professor Jolly extremely wrong indeed. Yet it was five more years before the profundity of Planck’s discovery was made clear. The year when physics was changed forever – 1905 – a year which stands as probably the most important and extraordinary year in the history of science. In the space of twelve months Albert Einstein published four academic papers that were so extraordinarily brilliant, and so universally disruptive, that they changed the field of physics almost beyond recognition. And at this point in the story, they very much deserve our attention.

Einstein’s life story is very well covered both in biography and fiction. In the spring of 1905 he was living and working in the Swiss city of Bern, looking after a new-born son and working as a patent officer. Just

65 Quoted from a lecture Planck gave in 1924, which was later quoted in Scientific American magazine, Feb 1996.
ten months later he would be receiving an honorary doctorate from the prestigious University of Zurich, and would be celebrated as one of the most important minds in all of physics.

The first of Einstein’s four papers dealt with a subject that Newton himself had spent much of his life attempting to master – the nature of light. Einstein published this work on June 9th 1905, and in one single document he provided explanations for two of the most puzzling discoveries in the world of optical physics. In particular, he attacked a problem known as the photoelectric effect. The discovery of this effect stretches back to Heinrich Hertz, whom we met earlier for his work on the discovery of electromagnetic waves in the late 1880s. Hertz showed that shining a source of ultraviolet light on two charged plates triggered sparks between them. He also discovered that shining light of a longer wavelength (and hence lower energy) does not trigger this effect, no matter how powerful the light source. With ultraviolet light, if you double the intensity, you double the current generated. With longer wavelength light, you never see any current generated regardless of how much light you shine on the target.

The effect was a curiosity, but Hertz died before it was explained in a paper that shook the world of physics. He went to his grave oblivious to the revolution that was coming. Around the year 1875, he wrote

“Sometimes I really regret that I did not live in those times when there was still so much that was new; to be sure enough much is yet unknown, but I do not think that it will be possible to discover anything easily nowadays that would lead us to revise our entire outlook as radically as was possible in the days when telescopes and microscopes were still new.”

Hertz never lived to see his pessimism disproved, but equally he never discovered an explanation for the strange results that he had witnessed.
Einstein, however, realised that there were important lessons to be learnt from Hertz’ discovery, yet his stroke of genius was in perceiving how it related to Planck’s discovery of the Black Body radiation law. The reason why Planck’s simplification – assuming, for the sake of easier mathematics, that light could only be emitted in discrete energy levels – happened to work so well, was that it was literally true. It wasn’t just an approximation that made the numbers match, it was an underlying truth about the nature of light and energy itself. Light can only exist with certain specific levels of energy, and therefore only at specific wavelengths. Those levels are very close together, so it appears to us like a smooth continuum, but it isn’t.

In Hertz’ experiment, incoming light strikes the atoms of the metal plates. If the light has enough energy – i.e. if it has sufficiently high frequency (remember – higher energy means more vibrations means higher frequency) – then it can knock an electron completely out of the atom. Free electrons carry electric current, and hence this new electron causes the current carried by the electrode to increase. If the incoming light doesn’t have enough energy, then it won’t knock the electron out of its parent atom, the energy will be absorbed and re-emitted as light, and no current will be generated. It doesn’t matter how much low-energy light you shine at an object – the energy is always insufficient to dislodge an electron and cause the current to flow. But the only way that could possibly be the case was if light existed in discrete packets. These packets were called “quanta of light”, and hence the “quantum theory” was born. If that were not the case then shining ten times as much light should always increase the current generated ten times. Even though longer wavelength light has a lower energy, it should have been possible to pick a light of half the energy and shine twice as much of it and get the same results. Hertz’ experiment proved that this was not the case, and Einstein showed why.

Perhaps the easiest way to understand this is by analogy. The original theory of light suggested that light was much like water – shining more light should have been like turning up the flow on a fire hose. If you get
a hundred small streams and feed their flows together, then you end up with a raging torrent of water that could overcome any barrier.

Light, it turns out, isn’t like that. Imagine instead you are at a fairground and you spot an intriguing game. The trick of this game is to throw tennis balls through a series of holes in a wooden board a certain distance away. You’ve got a reasonably good throwing arm so you have a go. You throw ten balls and five of them go through the holes. Congratulations – you win a cuddly toy. Sensing that you might have discovered a hidden talent, you pay for another ten balls, and you might reasonably expect that you would get roughly another five points. And so on – you could buy another ten, a hundred, a thousand balls and you would imagine that you would score points with roughly half of them, so buying ten times as many balls should net you ten times as many points. And by this stage you would be drowning in cuddly toys.

Now let’s imagine instead the owner of the game sold you slightly larger balls to throw. So large, in fact, that they were too large to fit through the holes in the board. You could throw ten balls and not get a single point. Tough luck, you might imagine, and you would buy another ten. Ten more failures. In fact, no matter how much you paid, and how many attempts you took, you would never score a single point with the larger balls because they physically couldn’t fit through the holes. In fact, if you were given a range of different balls, you would discover than anything over a certain size would never ever score a point, but that balls small enough to fit through the holes would occasionally score you points, and if you threw ten times as many balls, you would score ten times as many points.

The same is true for these packets of light, or photons. If a photon doesn’t have the energy to dislodge an electron, it never will, no matter how many times it tries or how many similar photons you shine at the atom. If you shine lots of photons together, they don’t ‘gang up’ to dislodge electrons in bulk.
All of this, of course, went against everything that science had assumed for the preceding century. In fact, though he had laid the groundwork for this discovery, Planck himself found Einstein’s discoveries profoundly troubling.

“It seems to me that regarding Einstein's corpuscular theory of light the greatest caution is to be advised... the theory of light could be thrown back not only for decades, but centuries”

Einstein himself spent much of his later life opposing the more esoteric later findings of quantum theory, but this first insight was undeniable and subsequent experiments showed his ideas to be correct. Five years after his paper was written, he even persuaded Planck of that fact. They later worked together on a great many important discoveries, having put aside their initial disagreement. The hallmark of a great scientist is that he or she should adhere to the principles of scientific scepticism: always require adequate evidence for any claim, but be willing to abandon any belief, no matter how strongly it is held, if sufficient evidence to the contrary arises.

So we’re not quite half way through 1905 and Einstein has just founded the field of quantum mechanics. One paper down, three to go.

The second of the papers, and perhaps the least well-known of the four, finally hit the press on July 18th 1905. It concerned the puzzling phenomenon of Brownian motion. This was the remarkable observation that very small particles, such as dust or pollen, when floating in a fluid such as water, tend to bounce around erratically, even in the absence of any air current to disturb them. It’s almost like tiny microscopic creatures are playing pollen football before your eyes.

Einstein showed that this process was caused by random movement of atoms within the water, and proved the plausibility of his theory with an argument based on statistical mechanics (the same field used by Planck
to derive his black-body radiation law). Both of these topics – the existence of individual, particle-like atoms, and the strange mathematical formulations of statistical mechanics – were controversial, and Einstein’s paper neatly combined the two, proving the validity of both and solving a long-standing problem in physics in one fell swoop.

So we’re not quite seven months in, barely over half way through 1905, and now Einstein has confirmed the truth of atomic theory and statistical mechanics in one single work. Two down, two to go.

The third and fourth papers (September 26th and November 21st) can really be seen as two aspects of the same work, and they describe the discovery for which Einstein is perhaps most well-known – his Special Theory of Relativity.

Relativity is such a famous theory that most people can name it, which is unusual for such a tortuously mathematical field. Though it’s probably fair to say that most people who can name it would understandably struggle to explain what it’s all about. Yet although the conclusions of relativity are mind-bending in the extreme, it actually stems from two simple postulates, or propositions, that anyone can understand. They are so fundamental that Einstein placed them on the first page of his famous 3rd paper of 1905, “On the Electrodynamics of Moving Bodies”.

**Postulate 1:** The laws of physics are the same for every non-accelerating observer.

**Postulate 2:** The speed of light has the same value for all such observers.

They seem innocent enough. The first is at least plausible – after all, I would be surprised if I were to measure the Universe behaving differently based on where I was located, or how fast I was travelling.

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Though that might not seem immediately obvious, remember that you are not, in fact, currently at rest – you are on a vast planet which is rotating at roughly one revolution per day, orbiting the sun at one orbit per year, at an orbital speed of 30 kilometres per second, and orbiting the centre of our galaxy at 200 kilometres per second. And then our galaxy is moving relative to other galaxies, and those galaxies relative to the rest of the Universe. So in no way does it make sense to say that the Earth is “at rest”. You could define it to be so, of course, but that would be a particularly strange way to see the Universe – akin to the pre-scientific geocentrism that Copernicus did away with in the 16th century.

Moreover, if you now left the Earth and moved to a planet orbiting a different star in a different galaxy, our relative motions would be phenomenally large due to the random drift of galaxies and the orbits of the various stars. Yet I’m willing to bet that you would still expect falling objects to obey the law of gravity, and water to be composed of two atoms of Hydrogen and one of Oxygen. You would still expect to be able to breathe Oxygen and exhale Carbon Dioxide, and you would still expect fire to feel hot and ice to feel cold. In fact, with modern astronomy we can actually observe the consequences of various laws of physics at vast distances by examining highly luminous events like supernovas. These experiments so far have shown that all laws we can reliably test are the same wherever we test them. So Einstein’s first postulate looks solid.

Now if you accept the first postulate then the second actually leads from it. After all, the speed of light is merely, as Maxwell showed, the consequence of the laws of physics. Light is an electromagnetic wave, and its speed can be derived directly from his famous equations which describe how electric and magnetic fields work. So if the laws of physics are identical for any two observers, then the speed of light should also be identical for them both.
That perhaps seems acceptable, and by now I hope that I’ve convinced you to accept tentatively Einstein’s two foundational postulates. That might not seem very controversial, but this is where I admit that I’ve tricked you into accepting all of relativity. Let’s just look at what the postulates imply: Imagine we are piloting a spacecraft travelling through space at high speed. Let’s say we shine some light out in front. Maybe we fire a laser, for example. The laws of physics say that the speed of light must be the same in all reference frames (ignoring acceleration for now as this complicates things). So we know how fast this light is moving away from the spacecraft – it’s moving at the speed of light, commonly known as ‘c’.

Let’s say the second spacecraft intercepts this light beam. Again, the speed of light is constant everywhere, so spacecraft 2 measures this light travelling at the exact same speed ‘c’, just like the first spacecraft. But that’s really weird, if you think about it, and I can show you why by slightly altering the picture.

Let’s say instead that these two spacecraft are travelling directly towards each other in some futuristic game of chicken. And let’s say that instead of light, the first spacecraft fires a missile, and measures that missile travelling away from it at a speed of 100 metres per second. Let’s say the second spacecraft is moving directly towards the first at a speed of 200 metres per second. Now from the perspective of the second spacecraft, the missile is moving towards it at 100 m/s faster than the spacecraft that fired it. When we add together 100 m/s (the speed of the missile relative to the first spacecraft) plus 200 m/s (the relative speed of the two spacecraft), we see that the second ship should measure the missile moving at 300 m/s towards it – in other words, it measures a different speed for the missile than the first spacecraft does, because the spacecraft are moving relative to each other.

This, I think, is intuitively obvious – if you fire a missile at a target, then the missile is moving away from you at a certain speed. But the speed at which it is approaching the target depends not just on the speed
of the missile away from you, but also the relative motion of the target. Yet the remarkable thing is that, as I stated earlier, this doesn’t happen with light! And we know this because the speed of light must take the same value for all observers. So if we go back to our spacecraft and replace missiles once more with laser beams – in this case, the second ship measures the light travelling at exactly the same speed that the first ship does.

It is almost impossible for me to describe how weird this revelation actually is. Imagine a train travelling rapidly down a track and a man walking through the train in the direction of travel at a gentle pace. His fellow passengers would see him walking at, well, walking speed. Yet an observer on the side of the tracks would measure the man travelling past slightly faster than the train itself. Yet somehow, if we replace the walking man with a packet of light, then the observer on the side of the track and a passenger inside the train would both measure the light moving at the same speed.

Something was going very wrong here with the existing picture of physics. The conclusion of Einstein’s Theory of Relativity is perhaps even more disturbing than that of quantum mechanics, because it deals with objects that we can see and which we think we understand. In fact, the only way to explain why observers always measure the same speed of light regardless how fast they may be travelling relative to any fixed reference, is that they must measure time differently. An observer approaching the speed of light measures time passing at a different rate compared to observers moving relative to him. And because the speed of light is a constant, that means that a moving observer must also measure distance differently, too. After all, if you measure a light beam travelling for a second by your own clock, you know how far it has gone (one light second). But an observer moving rapidly relative to you will measure that second differently. Yet the speed of light is the same, so the distance he measures will be different.
Einstein’s theory of Special Relativity was widely acknowledged but rarely understood. The physicist Ludwik Silberstein relates how, during one of the lectures given by British Astrophysicist Sir Arthur Stanley Eddington (1882 – 1944), he enquired concerning this new scientific revolution. “Professor Eddington, you must be one of three persons in the world who understands general relativity.” Eddington paused, unable to answer. Silberstein continued “Don't be modest, Eddington!” Finally, Eddington replied “On the contrary, I'm trying to think who the third person is.”

No doubt, if you had not previously heard an explanation of relativity, you are probably now thinking something along the lines of “that’s just daft – time is time, and it can’t somehow run at a different speed for different people.” Well, it turns out that you can’t escape Einstein’s remarkable discovery. In the century since Einstein first proposed the theory that I have just described, his insight has been proved correct many times, to extraordinary levels of precision.

One man, one year, four papers, two profoundly important revolutions.

The Theory of Relativity is an extraordinary work of genius, and is perhaps one of the greatest ever accomplishments of the human mind. In fact, in the space of twelve months, Albert Einstein had ushered in a revolution comparable to the ones Newton generated by the publication of *Principia Mathematica* and *Opticks* together.

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Relativity continued to develop over the next few decades. In 1915, ten years after his papers on Special Relativity, Einstein published a set of four follow-up papers in which he introduced the *General Theory of Relativity*, which tied up one remaining hole in special relativity. Remember when I said about Einstein’s first postulate that it only worked when the observer wasn’t accelerating? Well General Relativity allows us to remove that caveat. It took ten years because, as it turns
out, this isn’t a trivial thing to do. Yet despite all the complexity, Einstein’s Special and General Theories of Relativity are still used today at the cutting edge of research in all branches of physics from Cosmology and Astrophysics down to Nuclear and Particle physics, and every scale in-between. Einstein’s theories have withstood the test of more than a century of the most rapid and profound scientific change in human history, and they have come out entirely unscathed.

Yet the story was different for quantum mechanics, which was due to suffer a sizeable change of direction in its infancy. This new field of learning started off as a reasonably straightforward new science, which posed several substantial new mysteries, but did not diverge too strongly from what had come before. Indeed, for roughly twenty years, the understanding that energy can only be found in discrete chunks continued to shed new light on a wide range of hitherto unknown or unexplained phenomena. But there were still one or two threads dangling from the fabric of even Quantum Mechanics and, in 1924, the French physicist Louis de Broglie (1892 - 1987) pulled on one of those threads, in his PhD. thesis, no less.

The problem was this: Newton originally proposed that light was composed of small particles or *corpuscles*. Yet several studies performed in the early 1800s had led most physicists to conclude that Newton was wrong. So Newton’s ideas were thrown out in favour of the *wave theory* of light. But then came Einstein with his paper on the photoelectric effect, which showed once more that light was composed of particles – vindicating Newton’s corpuscular theory. Yet the experiments that proved the wave theory still stood – nobody could work out what was wrong with them. Surely one picture had to be correct, and one false. It was just a matter of working out which set of experiments was wrong, and why.

De Broglie had a better idea. He made the bold suggestion that perhaps light was both a particle *and* a wave – sometimes exhibiting one set of properties and sometimes the other. It sounds ridiculous, but the
evidence in support of both sides of the debate was substantial and undeniable, and something had to give. In this case, the losing party was human intuition. De Broglie’s suggestion was indeed simple and explained the observations, but it went profoundly against the intuitive picture of physics that had been followed up to this point.

De Broglie’s work unleashed a torrent of activity. In rapid succession a number of other physicists took his ideas and ran with them far beyond anything that de Broglie himself had ever intended. This period of discovery was so intense that physicists tend to delineate the “Old” quantum theory up until around 1925, from the later work which started with De Broglie’s extraordinary thesis. It is almost as if they belonged to two entirely separate fields of research.

This new phase of quantum mechanics was to provide ample intellectual confusion for many extraordinary minds, though perhaps the most important was Erwin Schrödinger (1887 – 1961) who, in a period of frantic productivity in 1926 that rivalled Einstein’s annus mirabilis of 1905, published four papers in quick succession in which he laid out his formulation of the new field of wave mechanics. Schrödinger realised that particles – in the sense that we perhaps think of them as tiny billiard balls bouncing around in space – do not exist. Despite the many pages I’ve written on the atomists and the work of Thomson and Rutherford, it turns out that the atomic model they built is only really an approximation of what’s really going on behind the scenes. It’s a simplification, an analogy, but not literally and completely true.

Schrödinger knew that it was time to break completely with the old world that had dominated physics up to this point, and break out in a new direction. He put forward a new postulate of quantum mechanics, completely without any justification whatsoever, and began to investigate its implications. Schrödinger’s claim was that any quantum mechanical system can be fully described by performing mathematical operations on that particle’s underlying wave equation – a mathematical formula that encapsulated every aspect of the particle’s present state. In
one sense it was just a mathematical gimmick which opened up a new way of looking at the physical world – but Schrödinger knew that it was actually very much more than this – physics and mathematics were beginning to blend into one, and the closer we looked at particles, the less they seemed to exist in any literal sense and the more they became mathematical side-effects. Just as Planck’s almost accidental use of quantisation proved to reveal some fundamental truths about the nature of matter and energy, so too, this new way of thinking was more than just a casual trick. In fact, it was unlike anything that had ever been called physics before. It was bold and terrifying.

Accepting Schrödinger’s formulation meant discarding any hope that physics was once more nearing its cosy conclusion. For the first time in the history of mankind we were forced to make a startling sacrifice: In order to understand the Universe truly in all its intricate glory, we needed to let go of that most cherished component of any relationship – trust. We could no longer trust our brains to deliver the answers, because our brains had evolved to understand a world that no longer existed. In fact, it turns out, it had never existed.

I still find this whole concept unsettling, as I imagine you do. We’re in good company, as it happens. Celebrated Austrian Physicist Wolfgang Pauli (1869 – 1955), himself later to become one of the most influential names in Quantum Theory, was deeply disturbed by the direction that the subject was taking, and admitted as much in a private letter to a friend:

“At the moment physics is again terribly confused. In any case, it is too difficult for me, and I wish I had been a movie comedian or something of the sort and had never heard of physics.”

66 Wolfgang Pauli, quoted by Thomas Kuhn in his Structure of Scientific Revolutions, 1962

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Einstein himself was experiencing similar thoughts throughout the development of the quantum theory. In his autobiography, he reveals his worries:

“All my attempts to adapt the theoretical foundation of physics to this knowledge failed completely. It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built.”67

With Schrödinger’s work, all of a sudden, nothing was real – there were no particles, no atoms, no photons or electrons – nothing actually existed as a concrete physical entity. All that we see is the result of uncountably many overlapping probability fields. Reality, it turns out, is entirely built from numbers.

Of all the discoveries that science has ever provided, the advent of modern scientific thought in the first half of the Twentieth Century has been by far the most significant and poses the greatest challenge to the scientific community and its relationship with the general public. After so many fruitful centuries of progress wrought by extraordinary, pioneering minds, it was almost as if the natural world was forcing us to throw it all away – not just the theories, but the processes, the intuition, the mental constructs and the rational assumptions on which all of science had been built.

This brave new world was not a place of peace and contentment; it was a purgatory of confusion and despair. How things had changed from Newton’s simple, classical view of the Universe where God slotted all the parts together like a clockwork machine – to this modern view where nothing was real, even time and space were in perpetual flux, and the true workings of the Universe now seemed further from our grasp than ever before.

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As the celebrated Danish Physicist Niels Bohr once said, “anyone who is not shocked by quantum theory has not understood it.”

The main casualty of this new century of scientific revolution was undoubtedly the Gentleman Scientist – that familiar figure who has filled the majority of the previous chapters, but who largely dies out by the beginning of the Twentieth century. The inquisitive dabbler, the wealthy private scholar, the insatiable polymath who builds his own laboratory, pours chemicals into labelled flasks, heats them, electrifies them, measures the residue and, when night falls, points his telescope excitedly heavenward – this character has been confined to history. He has made his mark and stepped back. Science is now the realm of the professionals – there is simply too much background reading, too much mathematics, and far too little nuts-and-bolts-experimentation for the kind of intrepid intellectual explorers who dominated the field of learning up to this point. Einstein, initially an outsider, is rapidly subsumed into the academic edifice, where colleagues like Planck and Eddington were already making their mark.

Yet with the rise of the professional scientist, a void began to open between the scientists and the lay public. Until this point, scientists were seen rather like artists or musicians – as individuals with particular talent and dedication, but still working with a subject that the public could understand and could dabble in, without as much success perhaps, but with at least recognisable results. After all, anyone could combine a few chemicals, carefully measure the mass of the results and perhaps take notes about changes in colour or smell. Anyone could grow pea plants and count how many of their offspring had long or short pods. But by the inter-war period – especially in the 1920s – we began to see the beginning of a sort-of scientific priesthood, formed of obsessive career-scientists who studied for year upon year to master the study of their chosen field, and then mixed almost entirely with other experts.

68 “The Philosophical Writings of Niels Bohr” (1998)
discussing the finer points of their unfathomable obsessions in terms that the layperson could never hope to grasp. The only vague glimmer of hope was that scientific papers were now at least usually written in the Scientist’s mother tongue, instead of Latin\(^{69}\) - but it was not enough.

Despite this welcome move from the language of the highly-educated elite to the language of common folk, science was disappearing from the view of non-scientists because it had come so far from the intuitive, and had done so more quickly than society could adapt. Science – or at least physics – became less about stories and experimentation, and increasingly more about ploughing through page after page of dense mathematics, out of which morass only the very brightest and most able minds could ever draw any semblance of meaning.

Newton’s experimentation had involved prisms and lenses. Franklin used kites flying in storms. Darwin studied finches, and Rutherford shone particles at a strip of golden foil. But here, in this new world of general relativity and quantum mechanics, we find ourselves in a world whose basis is not in concrete experimentation or observation, but in the fiendish study of tensor mathematics, partial differential equations, Hermitian operators and covariant transformations. Black Holes (of which more later) were first discovered entirely from the mathematics of special relativity, and partly because of their purely theoretical discovery, the great Eddington himself famously refused to believe the conclusions, labelling the theory “stellar buffoonery”. He was one of the last of a dying breed.

Indeed, philosopher and historian Thomas Kuhn (whom we met earlier) in his profoundly influential 1962 work, “The Structure of Scientific Revolutions”, summarises the alienation wrought by this rapid progress in the acquisition of knowledge.

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\(^{69}\) In fact, this change could potentially be traced back to Newton himself. His Principia was published in Latin in 1687, but in 1704, his second great work, Opticks, was published in English.
“Both in mathematics and astronomy, research reports had ceased already in antiquity to be intelligible to a generally educated audience. In dynamics, research became similarly esoteric in the later Middle Ages, and it recaptured general intelligibility only briefly during the early Seventeenth Century when a new paradigm replaced the one that had guided medieval research. Electrical research began to require translation for the layman before the end of the Eighteenth century, and most other fields of physical science ceased to be generally accessible in the Nineteenth.”

By the time of the new Quantum Theory, not only were the results not generally accessible, but they were only barely accessible at all, and even then only to a tiny core of brilliant, highly dedicated specialists.

It is almost certain that Isaac Newton, at this stage in our journey, would feel more uncomfortable than at any point before. It is now where he would object to our story, where he would fight against this new mode of thought, where he would denounce, and where he would resolutely refuse to believe – as even Einstein did in his later years – that the Universe could be so complex, so tortuously and needlessly obscure.

For Newton, science was all about understanding the mind and nature of God, and unravelling the deity’s plan in the Universe. Newton believed very strongly that there were underlying laws to be discovered – the mechanism by which the Almighty achieved his plan – and that those laws should be simple, concise, even beautiful.

“It is the perfection of God's works that they are all done with the greatest simplicity. He is the God of order and not of confusion. And therefore as they that would understand the frame of the world must indueavour to reduce their

70 Thomas S. Kuhn, “Structure of Scientific Revolutions”, 1962
knowledge to all possible simplicity, so must it be in seeking to understand these visions. And they that shall do otherwise do not onely make sure never to understand them, but derogate from the perfection of the prophecy; and make it suspicious also that their designe is not to understand it but to shuffle it of and confound the understandings of men by making it intricate and confused.”

In Newton’s lifetime, and indeed for over a century and a half afterwards, it looked like this picture was holding up to scrutiny, with successive advancements filling in gradually more and more of the scientific picture of the Universe. Yet Einstein and Planck, and the theories spawned by their extraordinary discoveries, overturned all of this. The hope that the Universe might be understood by a few simple, constant and self-evident laws – the celestial toolbox – had faded forever from sight.

Though he did not believe in a creator deity, Einstein himself was also troubled by the lack of order and predictability that the new Quantum theory had unleashed. In one of his most famous quotations, writing to his friend Max Born in 1944, he reveals his frustration.

“You believe in the God who plays dice, and I in complete law and order in a world which objectively exists, and which I, in a wildly speculative way, am trying to capture. I firmly believe, but I hope that someone will discover a more realistic way, or rather a more tangible basis than it has been my lot to find. Even the great initial success of the quantum theory does not make me believe in the fundamental dice-game, although I am well aware that our younger colleagues interpret this as a consequence of senility.”

71 Isaac Newton, Rules for Methodizing the Apocalypse, Rule 9
72 Max Born, “The Born-Einstein Letters” (1971)
Perhaps the most difficult transition that occurred in physics during the early Twentieth century was not the dramatic rise in the complexity and costs of scientific experiments, but the fact that the cutting edge Science was not only unintuitive, but extremely difficult to demonstrate to non-experts. Newton could just set up a prism and a light source to observe the spectrum, and Galileo could drop objects of varying masses from a tower and see which one hit the ground first. Yet Quantum Mechanics deals with the ungraspably miniscule, and relativity with vast cosmological distance scales or unimaginably high speeds. They are mind-bending disciplines, best understood through mathematics and, hence, for the majority of the population, not understood at all. Which makes it incredibly difficult for scientists to explain what they are doing to the wider world, and (perhaps more importantly) to those who are holding the purse strings.

This whole issue stabs deeply at the heart of the scientific endeavour and forces us to start asking difficult questions of the scientific establishment itself. By the point at which research into Quantum mechanics became most feverishly active pretty much all big-ticket science was funded by governments. This has continued, amplified even, to this day. Debate is flourishing in the 21st Century concerning the degree to which scientists, funded by government grants, should study only those topics that look like they will deliver politically valuable results. In today’s world we think of cutting-edge medicine, intelligence and surveillance, defence, computation and electronics. Yet how can anybody predict where the more esoteric branches of scientific research are going to lead? After all, I doubt that even the most prescient of American Presidents, eager to discover newer and more powerful weapons of war, would have realised that Einstein’s 1905 work on the curious theoretical properties of light would, in just 40 short years, lead to the creation of the most devastating destructive weapon ever created.

In the 2008 US Presidential election, gaffe-prone Republican Vice-Presidential nominee Sarah Palin commented on how governments are
wasting their money on seeming irrelevances such as “fruit fly research”. As it happens she picked a particularly irresponsible example – research on the common fruit fly *Drosophila melanogaster* forms the cornerstone for vast swathes of modern genetic theory because they happen to have a remarkably simple genetic code and they breed rapidly. In some sense Palin couldn’t have been expected to know that. But then again, she was making a statement about the sort of things scientists should be studying, and she was in the running for the vice-presidency where she would be a heart-attack away from holding the most powerful office on Earth.

We elect our politicians as leaders of our nations, but not as omniscient oracles of all knowledge. The focus and direction for scientific research is best decided by the scientists themselves. Short-term financial benefit is not the single most important consideration that a government should be taking into account when deciding where to inject our tax money. Einstein could never have known when he was working on his Special and General Theories of Relativity, that dozens of years in the future our aircraft, cars and mobile telephones would contain devices that use exquisitely accurate signals from satellites flying thousands of kilometres above our heads to determine exactly where we are on Earth to within a precision of a few metres. But yet the Global Positioning System (GPS) can only do this because it takes into account Einstein's theories (general and special relativity) to correct for the effects of speed and acceleration on the ultra-precise atomic clocks they contain. Without those corrections, the system would be entirely useless.

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I have said a lot in this chapter about how 20th Century science moved away from simple, intuitive investigation, and delved into the esoteric and mathematically obscure. Yet even at the birth of Einstein’s extraordinary discoveries, the human mind still played the starring role. Einstein’s great genius lay in discovering the remarkable truth of Special relativity before he had really worked through the mathematics.
He did it merely by thinking – by finding the right picture, the right analogy to apply to the physical world that could map the complex world of light beams into simple terms that his brain could handle. In fact, this one virtue is a common feature in nearly all the great minds of twentieth Century physics – of which Einstein and, later, Richard Feynman (1918 – 1988) are perhaps the two greatest examples.

Another fine example of the Scientific educator was the Ukrainian physicist, George Gamow (1904 – 1968), who held a number of prestigious positions across the former Soviet Union before fleeing to the West in 1933 to work with Marie Curie and Ernest Rutherford, amongst others. Gamow’s work covered a wide range of disciplines from cosmology to genetics, but perhaps his best-known accomplishment was in penning a series of popular science books in an attempt to explain the most complicated scientific theories of his day to the lay reader. The books recount the fantastical dreams of the eponymous hero, Mr Tomkins, who imagines extraordinary worlds in which the laws of physics have been changed in order to make relativistic or quantum-mechanical effects visible on a human scale. In one of Mr Tomkins’s first encounters, he explores the theory of relativity by imagining a world in which the speed of light is greatly reduced.

“A single cyclist was coming slowly down the street and, as he approached, Mr Tompkins’s eyes opened wide with astonishment. For the bicycle and the young man on it were unbelievably shortened in the direction of the motion, as if seen through a cylindrical lens. The clock on the tower struck five, and the cyclist, evidently in a hurry, stepped harder on the pedals. Mr Tompkins did not notice that he gained much in speed, but, as the result of his effort, he shortened still more and went down the street looking exactly like a picture cut out of cardboard.”

73 George A. Gamow, “Mr Tomkins in Wonderland”, 1940, Cambridge University Press.
Though cutting-edge physics was now directly inaccessible to all but the most dedicated expert, Gamow had stumbled on a way of getting across most of the key ideas in a way that the human mind could visualise and understand. The American astronomer Percival Lowell (1855 – 1916), once stated that “Imagination is as vital to any advance in science as learning and precision are essential for starting points.” And that was Gamow’s gift.

The great power of science is not in the complexity of its theories, or the technical marvels with which we now probe the Universe around us, but it is the simplicity of the process by which these discoveries have been found. Though only a celebrated few can truly understand the deepest, darkest corners of relativity or quantum mechanics, anyone can understand the scientific method which enabled those extraordinary discoveries. More than at any other time, the first few decades of the 20th Century illustrated the power of one simple idea to overcome even the most deeply-held beliefs. Einstein showed that human perception is not the incontrovertible yardstick that once it was assumed to be, but that instead we should trust reason and evidence above all else, no matter how unpalatable the consequent discoveries might initially seem.

The early 20th Century wiped out much of the complacency that had been building within the physics community up to that point, and it has never returned to the levels it reached in the days of Rutherford and Thomson. Indeed, every passing decade now seems to highlight with even more clarity the sheer overwhelming enormity of the task ahead of us. Perhaps, then, it may come as no surprise to learn that only a few short years after Einstein’s remarkable discoveries, and the birth of quantum mechanics, came a discovery from the field of Astronomy which would introduce human beings to previously unknown levels of humility. And it was the first of a series of discoveries that produce, even today, the greatest source of inspiration for the fertile imagination that human beings have ever conceived. Let’s take a look.
The Expanding Cosmos

“I keep the subject of my inquiry constantly before me, and wait till the first dawning opens gradually, by little and little, into a full and clear light.”

Newton

The history of humanity has been one of ever expanding horizons. The first hunter gatherers knew little of the world outside the valley in which they speared their dinner. Classical civilisations mapped out countries and continents, but they had scant awareness of the distant realms over which they held no dominion. By the middle ages, we were beginning to discover the extent of the world, confirmed its spherical shape and mapped out all the major land masses, though a few gaps still evaded even our finest cartographers. Renaissance astronomers attempted to go one step further by estimating the distance to the planets and the stars beyond, and Copernicus soon placed us very firmly not at the Universe’s direct centre. But it was in the 20th Century when we finally began to understand our true place in the cosmos and appreciate the immensity of the Universe that we call home.

Newton, together with Galileo and Copernicus before him, were collectively responsible for the first great shift in our perception of ourselves and our place in the Universe. The ancient, geocentric view put human beings at the centre of everything, immutable, stationary in space – the focus of creation. Copernicus’ theories showed that the Earth was not in fact in the centre even of the Solar System, let alone the entire Universe – instead, he realised that the Sun was the centre of
the Solar System, the planets all revolved around the sun, and the Earth was just one of those planets of the six that were then known, moving in great circles around our solar parent.

Newton extended this revolution by showing, as I covered in the first chapter, that one single unifying force – gravity – was responsible for moving these planets in their great paths in the skies, in exactly the same way that it caused apples and cannonballs to fall to the ground on Earth.

So the fall of geocentrism provided the first great shift. The second was that of Darwin, who brilliantly showed that human beings held no special, privileged place in the animal kingdom. Nor were we (or any animal) specially created for any purpose or reason, but we are the by-products of billions of years of random variation and blind, unplanned selection. So by the late 19th Century, we had discovered not only that we are not living in a special location, but also that we are not ourselves a special type of being – at least, not in any cosmic sense and certainly not distinct from the animals with which we share our planet.

These revelations would have been shocking and utterly unacceptable to Newton, but at least, by the end of the nineteenth century, humanity had experienced the last of the great shocks. Surely there was no hidden truth waiting to challenge our bruised egos? In 1888 the Canadian-American Astronomer Simon Newcomb (1835 – 1909) proudly proclaimed that “we are probably nearing the limit of all we can know about astronomy”. An astronomer of the late 19th century might quite plausibly have contended that humanity does indeed occupy a fairly privileged place in the cosmos because our solar system is situated at the very centre of the Universe.

That same Professor Newcomb, just 14 years later in 1902, delivered an address to the Astronomical and Astrophysical Society of America in which he admitted that he had completely changed his mind.

74 Pun fully intended

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“The nineteenth century, in passing away, points with pride to what it has done. It has become a word to symbolize what is most important in human progress. Yet, perhaps its greatest glory may prove to be that the last thing it did was to lay a foundation for the physical science of the twentieth century. What shall be discovered in the new fields is, at present, as far without our ken as were the modern developments of electricity without the ken of the investigators of one hundred years ago. ... What lies before us is an illimitable field, the existence of which was scarcely suspected ten years ago, the exploration of which may well absorb the activities of our physical laboratories, and of the great mass of our astronomical observers and investigators for as many generations as were required to bring electrical science to its present state. We of the older generation cannot hope to see more than the beginning of this development, and can only tender our best wishes and most hearty congratulations to the younger school whose function it will be to explore the limitless field now before it.”

The aim of this chapter is to explain the discoveries that led Newcomb to change his mind so dramatically and, perhaps more importantly, to introduce the remarkable and humbling research that Newcomb indeed did not live long enough to experience, but whose fruits we have the great privilege to experience and enjoy today.

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When we gaze up at the night sky on a clear night, we see countless pinpricks of light piercing the heavens, shining down on us from above. It seems obvious to us now that these are stars just like our own, though I challenge you, noble reader, to prove it by yourself. In fact this, I contend, is another one of those bits of knowledge that, when you really
look deeply at it, isn’t obvious at all, and the fact that pretty much everyone on Earth knows and understands it, hides a series of discoveries that took a great deal of effort and extraordinary ingenuity.

I don’t know if you have ever, as I have, found yourself in a public place, perhaps on a crowded train, alternately closing left and right eyes and trying to make nearby objects alternately obscure and reveal the items behind them. If you have ever done this, then not only will you have almost certainly had the experience of realising that the person just the other side of that same object now thinks that you are winking provocatively at them, but you will also have witnessed the phenomenon of *parallax*.

For a safer demonstration, parallax is the effect that you get when you hold up a finger at arm’s length and alternately close the left and right eyes while looking at it. The principle is exactly the same – the object close to you (your finger) appears to move relative to the background objects that are much further away. It’s not really moving, of course, it’s just that you are looking at it from two different angles.

This is all very well, but how does this relate to astronomy? Well it just so happens that parallax is the best way we have of calculating the distance between Earth and its nearest stellar neighbours. All you have to do is take some painstakingly accurate measurements and apply a bit of patience. Six months’ worth, to be precise.

Of course, we have to modify the whole “winking provocatively” process a little bit. For a start, we don’t just observe with our naked eyes but we use precise astronomical instruments to measure exactly where the stars appear to be in the sky. In astronomy we tend to measure the location of objects using a system of coordinates just like latitude and longitude on Earth, but projected on to the sky. That allows you to define precisely where an object is to be found in a way that all observers can agree on.
Secondly, we need to measure our nearby star against a much more distant background. In astronomy, we are spoiled for choice. For example, we could use stars that are known to be much further away through other means.

Thirdly and finally, we’re not just looking from the left eye and the right, but instead we’re using rather a longer baseline – in fact, we’re using one that is 300 million kilometres long, namely the diameter of the Earth’s orbit around the sun.

Other than these few changes, the process is identical. We measure the precise apparent position of some nearby star relative to the (distant, and approximately fixed) background stars. Then we wait six months, and measure the same star from the opposite side of Earth’s orbit. If the star is sufficiently close to us, then it will appear to have moved ever so slightly against the fixed background, exactly like your finger does when you look at it with alternate eyes. Then we apply a bit of high-school geometry, and out pops the answer – the distance to the nearby star.

This exact calculation was first performed in 1839 by the German astronomer Friedrich Bessel (1784 – 1846), narrowly beating competitors from Germany and Scotland who were attempting the same feat in the same year. Bessel’s measurements for the star 61 Cygni translated to a distance of a little over ten light years, and differ from the modern result by less than ten percent – a remarkable achievement considering he was measuring angles of about a third of an arcsecond. For reference, an arcsecond is $1/3600^{th}$ of a degree, which means that Bessel’s measurement is equivalent to standing on one side of a football pitch, and measuring the location of an object on the other side to within the width of a human hair. It turns out that astronomy is really hard.

Bessel’s results were a shock for many. It may seem strange to you now, but at the time nobody knew what stars were or how far away they were, but Bessel’s measurements showed just what had really been
hanging over our heads since our ancestors first gazed in wonder at the night time skies. The stars in the heavens were no mere celestial torches, but they were massive nuclear infernos, blazing with a brightness like that of our own Sun. Suddenly, with one realisation, we were no longer orbiting the only star that existed, but we had become the entourage of just one of countless millions of stars, some larger than our own and some smaller, but all made of the same stuff and burning with the same intense ferocity.

Of course this suggestion had first been made over two centuries earlier, at the turn of the 17th Century, by Italian polymath and Dominican friar Giordano Bruno (1548 - 1600), who had consequently been brutally murdered by the Catholic Church for that most heinous of crimes – being right in the face of dogma.

The measurement of stellar parallax was fiendishly difficult. So difficult in fact, that by the end of the nineteenth century, the number of stars with accurately determined distances still only numbered a few dozen. Once you start observing stars that are further away, the star appears to move by a much smaller distance. In fact, the parallax angle becomes so small that measuring it requires apparatus far beyond the technical capabilities of 19th century science. Today we have satellites that are capable of measuring stellar locations to quite astounding levels of precision. The GAIA satellite, launched in 2013, can measure to seven millionths of an arcsecond – or measuring an object the thickness of a human hair at a distance of 1,000 kilometres. If that doesn’t leave you speechless with admiration then I’m not sure what will. But such technological marvels are a relatively recent achievement and Astronomy couldn’t wait for instrumentation to catch up. So after the parallax method hit technical barriers, other mechanisms were needed to understand the composition of the heavens, and one such method was soon to come into its own.

The final proof, if any more were needed, that stars were very much like our own sun, came from a new field called spectroscopy. Spectroscopy
is what Newton performed when he directed sunlight through a glass prism in his rooms at Trinity College. Spectroscopes do with light what our noses do with smells. When you smell a familiar odour your brain subconsciously breaks it down into its constituent chemicals, works out how much of each chemical is present, and then checks in memory to see what that particular balance of chemicals corresponds to. In the same way, spectroscopy works by breaking light down into its constituent colours, seeing how much there is at each wavelength and then comparing it to known patterns. In the right hands, a spectroscope can reveal a great deal about the mysteries of the peculiar objects we find in space.

In fact, this one procedure has probably been responsible for more discoveries in the field of astronomy and cosmology of the last 150 years than any other single technology, because of the enormous wealth of new information it has revealed to us. In his address to the Astronomical and Astrophysical Society of America that we encountered earlier, Simon Newcomb highlighted the contribution of the spectroscope to the advances that were shaping turn-of-the-century astronomy.

“When, forty years ago, the spectroscope was applied to analyze the light coming from the stars, a field was opened not less fruitful than that which the telescope made known to Galileo.”

To understand why spectroscopy has been so invaluable, we perhaps need to look at why Astronomy is so hard in the first place.

Astronomy suffers from two rather profound drawbacks rarely experienced by other scientific disciplines. Firstly, it is impossible to set up your own experiment and measure the results – instead all you can do is open your eyes, look up and measure whatever the Universe feels like giving you on that particular day. Maybe nothing, maybe a supernova, maybe a solar flare, maybe something stranger. Secondly,
because astronomy deals with such enormous distances, it’s impossible for us to go over to nearby stars, let alone more distant objects, and measure them directly. We can’t take samples and bring them back to the laboratory for analysis. So instead we have to measure whatever we can from Earth. It’s like if you discovered that you had new next-door neighbours, and instead of popping round to say hello, you could only learn about them by rifling through their bins.

Because of these innate difficulties, astronomers are forced to be extraordinarily inventive and ingenious. The use of spectroscopy to study the nature of stars really took off in the mid-19th century and it allowed us to gain an extraordinary wealth of information about distant objects just by observing them carefully from Earth. Two pioneers of the technique were the husband-and-wife team of William and Margaret Huggins, a London-based couple who were the first to examine the spectra of some of the weirder objects in the night sky.

The sky isn’t just full of stars and planets – there are other more peculiar beasties out there too. The best-known list of such objects dates back to the turn of the 19th Century, when a Frenchman named Charles Messier (1730-1817) built up a catalogue of dusty clouds and clusters of stars which he observed through his telescope. Many of these objects had been known about for some time, but nobody really knew (or cared) what they actually were. In fact, Messier only bothered writing down their locations so that he could ignore them when hunting for comets.

William and Margaret Huggins thought differently, and suspected that these objects might be rather more interesting than everyone had assumed, so they started taking measurements of everything in Messier’s catalogue with their spectroscope to see if they could find anything novel. Some of Messier’s objects were indeed small clusters of stars, and unsurprisingly their spectra looked like those of other individual stars that had already been studied. The remaining objects on the list mostly appeared to be clouds of gas, and that is certainly what
they resembled through the telescopes of the time. Indeed, some of those ‘clouds’ gave exactly the results that William and Margaret Huggins expected from their spectroscope. But others didn’t look like clouds of gas at all. In fact, they had spectra just like stars. And that was very peculiar indeed.

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Thanks partly to the discovery of spectroscopy, astronomy progressed steadily well into the 20th Century. There were few enormous breakthroughs, but there was a lot of more steady, rigorous cataloguing and exploration to be done. After all, botanists and zoologists had spent centuries exploring the world’s flora and fauna, and categorising them into groups and species – astronomers had only just been given a technique by which to accomplish this, and they were making the most of it.

Yet in the years after the end of the First World War, a series of observations propelled a young American astronomer named Edwin Hubble (1889 - 1953) into the spotlight, and brought astronomy once again to the forefront of the human imagination. The name of Hubble is, of course, well-known to us today thanks to the extraordinarily successful space telescope named in his honour. But Hubble gained the right to have a telescope named after him thanks to two major discoveries that he made during the 1920s at the Mount Wilson observatory in California.

The Parallax method that we met earlier was, and indeed still is, an excellent method for determining accurate distances to nearby stars. But its main drawback is that it requires such extraordinarily precise measurements that it can only ever be practical for very nearby objects. The further away a star is located, the smaller the parallax and therefore the tinier the angle that must be measured accurately. In practice, even today, the most advanced satellite-based measurements that we make can still only map a relatively tiny number of nearby stars. The GAIA
I mentioned earlier is designed to do precisely this, and will vastly expand our knowledge of the location of the stars in our immediate neighbourhood – it plans to map approximately a billion of them. But even this extraordinary technological achievement still represents just 1% of our galaxy and nothing outside of it.

If we want accurate distance estimates to more distant objects, what we really need is a different technique altogether. It would have to work on just the brightest objects, because those are the only ones we can see at great distances, and we would have to calibrate it somehow using our existing parallax measurements of nearby stars as a baseline. By Hubble’s time there was no widely-used technique that could achieve what was needed, but there was this one idea that had recently been discovered by another American astronomer, Henrietta Swan Leavitt (1868 - 1921) in 1912 – seven years before Hubble first arrived at Mount Wilson.

Just as an aside, it is at the turn of the 20th Century that female scientists first start to play a substantial role in the field. Relativity and quantum mechanics remained heavily male-dominated for most of the 20th Century, but there had been female astronomers of note for many years – perhaps the most famous early example being Caroline Herschel (1750 – 1848), sister of the Astronomer Royal, Sir William Herschel. Caroline was a gifted astronomer, discovering eight new comets and producing a number of vitally important catalogues containing numerous stellar observations. She was honoured with the Royal Astronomical Society’s Gold Medal in 1828, a feat sadly not to be repeated by a woman until 1996. She was also the first woman ever to be elected an honorary member of that same society, in 1835.

Henrietta Leavitt was equally brilliant, and worked as an assistant to the American astronomer Edward Pickering (1846 - 1919), assigned to investigate the strange phenomenon of variable stars. Whereas most stars appear to twinkle when viewed from Earth, this is merely an illusion caused by the light from the star passing through the Earth’s
uneven and watery atmosphere. Variable stars are different – they are genuinely intrinsically variable, and their brightness changes sometimes over a period of a day or two, sometimes over several weeks, but usually in consistent and predictable patterns. The reason for this was not known in Leavitt’s time, and indeed isn’t fully known even today, but what Leavitt discovered was that for a certain kind of variable star, this pulsation seemed to be extremely consistent for each individual target, but varied widely between stars in a way that related closely to the star’s intrinsic brightness.

Leavitt used a simple trick to show this – she measured variable stars in the Large and Small Magellanic clouds. These are bright patches of light visible in the skies of the southern hemisphere. At the time they were thought to be nearby clouds of gas and stars. Whatever they were, it was a fair assumption that the Magellanic Clouds were small enough that all the variable stars within them were approximately the same distance from Earth. Given this assumption, Leavitt could “cancel out” the effects of distance, so to speak, and investigate the way that the stars’ apparent brightness related to the frequency of their variation.

Obviously the further away a star is, the fainter it looks, but stars are not all the same brightness. We can’t physically go over and measure each star close-up, so for any given star we don’t know if it appears bright to us because it’s nearby or because it’s just intrinsically a very bright object.

However, because these stars in the Magellanic Clouds were all at the same distance, two stars that appeared to be the same brightness must actually be of the same intrinsic brightness as each other. And when Leavitt examined the variable stars in these locations, she discovered that pairs of stars with the same peak brightness also tended to vary in brightness in a similar way. As the peak brightness increased, the rate of change of brightness decreased in a uniform and predictable way. When it came to variable stars of this type, the brighter they were, the more slowly they varied, and vice versa.
Leavitt’s discovery was fascinating, but sadly it wasn’t until 1922, the year after she died, when Edwin Hubble realised just how important her discovery had been. These variable stars are now known as \textit{Cepheid} variables, after the prototypical example of their kind called delta-Cephei and it just so happens that they are all intrinsically extremely bright, which is why Leavitt could see them in the Magellanic clouds, and it is also why Hubble attempted to pick them out in other nearby “clouds” from Messier’s catalog. By finding these extraordinary stars in distant objects, Hubble could measure the frequency with which their brightness varied, convert that to \textit{absolute} brightness, given Leavitt’s formula, and then combine it with the \textit{apparent} brightness to work out how far away they really were.

Let’s take a quick time out here and explain what’s going on a bit more carefully. Astronomy is a bizarre science because, as I’ve already said, you can’t choose your own experiments, and you can’t pop over and investigate the distant objects that you’re interested in. In fact, one of the biggest challenges in Astronomy involves working out how far away things are. It’s a pretty simple thing to measure on Earth, but in space it most certainly isn’t.

We’ve already met parallax already, which works very well for nearby objects, and now I’ve introduced the concept of variable stars. Parallax is a purely geometric method, but pretty much every other technique for measuring the distance to distant astronomical objects, including the Cepheid variable method, uses something called a \textit{standard candle}. The name is really quite a good indication of what I’m talking about here - we look for objects that have a known \textit{absolute} brightness. That is to say, if we were a fixed distance away from them, then we would know exactly how bright they should appear to us. Then if we can measure how bright they \textit{actually appear} to us, we can combine the two to work out how far away they are. All we need to know is that brightness falls off with the square of the distance, so if we move twice as far away, an object would appear to be $\frac{1}{2^2}$ or $\frac{1}{4}$ as bright. If we see an object that has
a certain brightness when it’s ten light years away, but we measure it at only a quarter of that brightness, then we know it must be 20 light years away. If it’s four times brighter than we would expect it to be at ten light years, then it must be five light years away. And so on.

This is exactly the same as the method we all use for estimating the distance to objects in our daily lives. For example, if you see a house in the distance, and you know roughly how big a house is, you can estimate roughly how far away it is. In fact, our brains do just this without even being asked. The problem in Astronomy is exactly the same as this, but with brightness instead of size. We could use apparent size as well, in theory, but there really isn’t much to choose from that has a well-known size. At least, not something whose size we could measure at a distance of millions of light years. So instead, we go for objects of known brightness and Cepheid variables were amongst the first of these standard candles ever discovered. They play a hugely important role in the history of astronomy because their brightness allows us to see them a long distance away. This means that we can accurately measure the distance to places in which they are found even if that distance happens to be very large indeed. And that is exactly what Hubble wanted to do.

The idea was exciting and all the necessary pieces were in place; all that remained was for Hubble to somehow calibrate the Cepheid relationship against a known distance – for example, the parallax measurements. Fortunately for Hubble, that hard work had already been done by the American astronomer Harlow Shapley (1885 - 1972). Shapley had taken Leavitt’s measurements, together with measurements from other variable stars, and had calculated the relationship between the period of a Cepheid variable and its absolute brightness. In other words, he had provided astronomers with a tool for going from a simple measurement (the rate at which a variable star changes in brightness) to a good estimate of its distance from Earth.
Shapley had already surveyed a number of nearby Cepheid variables and used their distances to estimate the size and shape of our galaxy. He discovered that the galaxy was rather larger than previously assumed – roughly 100,000 light years across, with a flattened disk in which most stars were located, and a broadly spherical halo all around it. The halo contains far fewer stars than the disk, but it does have a number of globular clusters – that is, dense groups of thousands of stars, bound to each other by gravity, floating alone through the depths of space. The Sun, far from occupying a privileged position in the centre, was banished roughly two-thirds of the way out along the galactic disk.

As it turns out, Shapley’s measurements weren’t tremendously accurate, but his numbers ended up in the right ball park. Nowadays, we have measured the disk of the Milky Way galaxy to between 100,000 and 120,000 light years across – very close to Shapley’s numbers – though only because Shapley incorrectly assumed that the halo defined the edge of the disk, which it doesn’t. The halo, in fact, extends a great deal further than this. He was also partly right about the sun’s location in the galaxy – we occupy an extremely uninteresting location at approximately 27,000 light years from the centre, on one of the spiral arms.

So by the 1920s, the work of Shapley and others had firmly established the extents of the known Universe, that is to say the Milky Way, as being roughly 100,000 light years across. The fact that the Sun wasn’t at the centre of the galaxy was not exactly welcome news to some – equivalent in some circles to the discovery that we were not at the centre of the Solar System. But it was nothing compared to the colossal shock that was about to come once Hubble published the extraordinary results of his own measurements.

You see, Hubble had decided to do something a bit different – instead of measuring stars that were scattered randomly across our galaxy, he decided to measure stars in the so-called Nebulae, or “clouds of gas” that Messier had catalogued over a century earlier. Discovering the
distance to these supposed gas clouds would help pin down their distribution throughout the galaxy and might tell Hubble something important about how our galaxy is structured. Yet they actually gave him rather more than he bargained for. In 1922, Hubble pointed his telescope at the so-called “Andromeda Nebula”, designated as Messier object number 31. Hubble discovered a number of Cepheid variable stars, and started measuring their variability in order to calculate how far away they were. It took a few months for the results to come in, but when Hubble finally finished doing the sums, the answer he had obtained was astonishing. If you remember, the entire Milky Way galaxy was expected to be roughly 100,000 light years across. Yet Hubble discovered that M31 was at a distance of one million light years.

For some reason, on discovering this extraordinary fact, Hubble took a route that is today the standard technique of charlatans and frauds – he decided to publish his results not in the peer-reviewed press so that his colleagues could properly scrutinise it, but in a commercial Newspaper. In this case, the *New York Times* of 23rd November 1924 under a wordy headline:

“Finds Spiral Nebulae Are Stellar Systems. Doctor Hubbell confirms view that they are “Island Universes” similar to our own”

Poor marks for misspelling Hubble’s name, but other than that, the article pretty much nailed the discovery. The reporter even continued with a stunning observation:

“This means that light travelling at the rate of 186,000 miles a second has required a million years to reach us from these nebulae and that we are observing them from the Earth by light which left them in the Pliocene Age.”

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75 Quoted in Sharov & Novikov (1993), Edwin Hubble, the discoverer of the big bang Universe (CUP)
221
In fact, Hubble’s observations were considerably smaller than the true figure – we now know that M31 is a galaxy roughly the same size as our own, and 2.5 million light years distant. We also now know that the Pliocene age ended roughly 2.5 million years ago, so it turns out that the journalist’s comparison was just about correct, but only because both numbers in it were wrong by the same amount!

The human mind, I am convinced, is incapable of grasping distances of light years. Light travels, as the article said, 186,000 miles per second, which works out at fractionally under 300,000 km/s. The sun is just over 8 light minutes distant, which means that it is 150 million kilometres away. If we scale the solar system down by a factor of a billion, we get a sun in the centre about 1.4 metres across, with Earth roughly the size of a small grape, 150 metres away. But even scaling down by a factor of a billion isn’t enough, because a light year on that scale is still 9,500 kilometres, or approximately the distance from London to Tokyo. But even the very nearest star (other than our Sun) is still over four times further away than this. 61Cygni – the star that Bessel famously measured with his first parallax study – would be a quarter of the way to the moon, and M31 – Hubble’s distant galaxy – would be four times further away than Pluto. Again, I remind you that this was scaling down by a factor of a billion.

You see why Astronomers use light years? I suggest we do the same. A light year, of course, is the distance travelled by light in a year, or slightly under ten trillion kilometres. Don’t try to picture it – I certainly can’t. And at this point I ought to highlight the obvious peril – a ‘light year’ is, of course, a measure of distance, not of time. I guess you could think of it like a “Walking Hour”, which might be a distance of five or six kilometres perhaps. Or maybe a “Usain-Bolt-second”, which is a little over ten metres.

When light left the Andromeda Galaxy (as it is now more properly known), the very first individuals of the Hominid genus were beginning
to arrive in continental Africa. Homo *habilis* was the bridge between our even earlier ancestors, Australopithecus *africanus*, and the first of our modern relatives that we might describe as more-or-less human. As the first few of these ape-like hominins roamed the plains of prehistoric Africa, a variable star in a distant galaxy was roaring with nuclear fire, spewing out a gargantuan amount of energy in visible light – photons, as we now know – and firing it across the Universe. A tiny fraction of those photons happened, just by chance, to be emitted in the direction of a distant galaxy that we know as the Milky Way; our home. This Cepheid variable star was far too young and violent to have any habitable planets around it, but perhaps elsewhere in M31 there were sentient life forms who would have witnessed our own galaxy in the dark night sky, a faint fuzzy patch in some alien constellation or other, an unimaginable distance away.

The photons sped away from their parent star until a few thousand years later, long after those original intrepid hominins on Earth had died and turned to dust, those same packets of energy finally left M31 and entered intergalactic space – the vast void of near emptiness between our two island Universes. The photons sped onwards, with their home galaxy gradually receding into the distance behind, and the Milky Way growing ever larger up ahead. A million years passed, then two (the photons didn’t notice, of course, as Einstein pointed out that at the speed of light your perception of time essentially vanishes). Back on Earth, the Homo *habilis* species was now long dead, replaced by Homo *ergaster*, Homo *erectus*, and eventually by a new, big-brained species we now know as Homo *sapiens*, who finally arrived on the planet as the photons were nine-tenths of the way through their journey.

Photons from that star had been sprayed all over the sky, but one just happened, by a fluke, to be aimed at that one distant galaxy, which it entered a few thousand years before the present day. By luck it was also pointed directly at a small Solar System 27,000 light years out from the centre, in which a relatively faint G2-type main-sequence star was busily burning away, gently warming its retinue of planets. The photon
travelled onwards, as human civilisation grew, great wars were fought, billions upon billions of human beings were born, lived, died and faded out of memory. In the year we now call 1922, the photon entered that same Solar System, whizzing past the outer planets before its fate became clear as a seemingly insignificant blue-green world grew ever closer, ever larger. Of all the many photons that were pointed at that same solar system, only a miniscule fraction were directed at that one planet. Yet shortly after the planet appeared in view, the photon entered that planet’s atmosphere and, in its few remaining microseconds, entered into history.

It turns out that the photon was not just aimed at our Earth, but was aimed at a certain part of our Earth in the United States. And it wasn’t just aimed at that region, but at a telescope in that region, and at the aperture of that telescope. And it arrived just at the right time; a few minutes earlier and the photographic plate might not have been exposed; a few minutes later and the photon might have slammed unceremoniously into the telescope dome. Of that photon’s companions – the countless other photons that accompanied it from M31 over those 2.5 million years, some stuck with it right up until the end. Many failed to make it through the atmosphere, some missed the telescope’s primary mirror, or got absorbed in the collision. But some – just a few – smashed into that large primary mirror, bounced off the secondary, and finally collided with a silver bromide emulsion that allowed one man to make a discovery that fundamentally changed our view of the Universe – us, the descendants of those same early hominins - who now look up at the night sky, our comprehension expanded in an extraordinarily profound and irreversible way by the photons who made that vast journey at just the right time.

When we look towards the constellation of Andromeda and, by chance, another photon that left less than a century later than those few that Hubble observed, happens to enter through the pupil of our own eye and strike our retina, we know the astounding journey that this packet of energy has taken. And more than that, we know that the Universe
itself stretches ten thousand times further even than the Andromeda Galaxy, with billions upon billions of other island Universes, each of them blasting ineffable streams of photons in our direction – countless untold stories travelling through the cold blackness of intergalactic space.

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Seventy-one years after Edwin Hubble published his extraordinary observations, a single image was created that captured the human imagination more than perhaps any other picture ever taken by any telescope in the history of the human race. The camera responsible was fitted to a telescope named after Edwin Hubble, and was orbiting in space, 560 kilometres above the surface of the Earth. The photo was a portrait of a tiny patch of sky, the same apparent size as a grain of sand held at arm’s length. The target was chosen because it was dark, boring, bland, lacking in any interesting features. Yet despite the apparent bleakness of the target, the photo itself was built up from 342 exposures, totalling almost six days of constant observation of the exact same insignificant speck of sky.

The story of the Hubble Deep Field image is perhaps well known. You have almost certainly seen it, with its familiar triangular profile (due to the arrangement of sensors on the camera with which it was taken). Yet the most striking thing about this one image is that it is teeming with colour, bursting with life from every single pixel, with galaxies of all shapes and sizes wherever you care to look. The handful of foreground stars from the Milky Way are spectacularly swamped and overrun by countless other objects, up to twelve billion light years distant. This one bejewelled image records light that left its source when our Universe was but an infant, just ten percent of its current age and long before our own Sun and the solar system it governs were even formed. Whenever I see this image, I think back to those first pioneers of microscopy, peering through their lenses for the first time at a seemingly uninteresting, sterile drop of water only to discover a microcosm of life within. Whenever we examine in detail even the most seemingly drab
and meaningless speck of our Universe, science somehow manages to pack it full of meaning, full of awe and resplendent with the most awe-inspiring and beautiful surprises.

![The Hubble Deep Field Image](Fig7.png) (Courtesy NASA)

In 1902, when Newcomb gave his now famous address, he was keen to point out that

“... as a general rule, there are no great agglomerations of stars elsewhere than in the region of the Milky Way.”
He could not have been more wrong. Yet I imagine, had he lived to learn of his ignorance, he would have been deliriously happy to gaze at that one celebrated portrait of deep space and contemplate with joy how much richer the Universe is than he had ever imagined.

Almost everything in the Hubble Deep Field image has been discovered since Hubble himself lived – in a way it is a biography of astronomy and cosmology for the last half century. Even the observation that the Universe is older than our own Sun is a remarkably new addition to the picture. Most educated folk in the 21st century would readily accept the evidence, but it would have seemed extremely strange to an Astronomer living in Hubble’s world, even as the story of distant galaxies became known.

After Hubble’s discovery, the astronomical world was in turmoil. One astronomer who was perhaps affected more than most was Harlow Shapley, whose work on Cepheids gave Hubble the tools he needed to make his discovery in the first place. Hubble wrote to Shapley in 1924 with his initial observations, and later followed up with more detailed analysis. Shapley had dedicated his early career to proving the falsehood of the galactic hypothesis – and firmly believed that all the so-called ‘nebulae’ were in fact nearby gas clouds attached to our own galaxy. He even entered into a famous public debate on the matter on April 26th, 1920, with the astronomer Heber Curtis (1872 – 1942). Hubble’s discovery conclusively proved Shapley wrong, causing Shapley to remark to a colleague that Hubble’s letter had “destroyed [his] Universe”. In the manner of a true scientist, Shapley accepted his error and changed his opinion. The ‘rules’ of the scientific method state that a belief should never be held longer than the evidence can support, and that theories in and of themselves have no value – it is only in the degree to which they correspond to reality that they should be retained.

As it happens, the story of the first measurement of galactic distances is one of two discoveries for which Hubble is rightly celebrated – the second, one might argue, was even more staggering than the first.
Except this time, it is a discovery that perhaps even Newton, the fanatical deist, might have enjoyed.

Once Hubble had published distance estimate to M31 and M33 (another nearby galaxy), others got in on the action, and started measuring distances to other galaxies using the same method. By the end of the 1920s, dozens of targets had been examined and were nearly all pushed out way beyond the bounds of our own galaxy. But Hubble was busy on another study – he was looking at the light from these same galaxies and measuring how fast they were moving through the cosmos.

Again, to the blackboard. I said that everything we know about Astronomy (more or less) we only know because we can measure it on Earth. I also mentioned that spectroscopy – that is, measuring the spectrum of light emitted by a distant star – was to become an extremely powerful and important technique as the 20th century took its course. Well here’s one of the main reasons why: it turns out that the light emitted by an object can be used to measure that object’s speed. And this is done by looking in the light it emits for certain fingerprints belonging to well-known chemicals, and by measuring how they change.

We learned last chapter about Max Planck and his law of black body radiation, which shows what an ideal emitter should look like when you examine its light in a spectroscope. It turns out that stars look pretty much like black bodies, once you measure their light outside of the influence of the Earth’s atmosphere. However, it also turns out that the spectra of stars aren’t quite as smooth as Planck would have you believe, and the main reason for that is that they are scarred with features caused by the peculiar behaviour of certain elements in the stars’ atmospheres. This is exactly what William and Margaret Huggins were looking for when they examined the spectra of objects in Messier’s catalogue.
Take our Sun, for example. The surface of our Sun is not actually a solid boundary, but rather a thick layer of superheated gas. Photons that reach the Earth have come from this outer layer, yet not all photons emitted from this region make it out unscathed – some of them collide with other atoms in the Sun’s atmosphere before they reach interstellar space. Those photons collide in a particular way that leaves a fingerprint that can be measured from Earth.

Let’s pick a certain element – let’s use Helium because it has an interesting place in this story. Now Helium, it so happens, consists of two protons, two neutrons and two electrons. It’s a simple molecule – only Hydrogen is simpler. Helium is hugely abundant in the Universe, inside all regular stars, but is very rare on planets like Earth because it tends to evaporate off into space at the slightest provocation. Now it turns out that Helium has a few specific characteristics, which come about as a feature of how the atom itself is put together. It just so happens that a Helium atom is particularly sensitive to photons with a wavelength of 588 nanometres (billionths of a metre), which is a sort-of yellowy colour. If a photon of that wavelength strikes a helium atom then it will be absorbed by the atom entirely. That energy might later be re-emitted, but that re-emission will happen in a random direction that almost certainly won’t align with that of the original photon. So this means that, if you observe a source of blackbody radiation hidden behind a cloud of helium, then you would see a dip in the intensity of light reaching you at roughly 588nm because many of those photons would have been absorbed by the Helium instead of passing through.

The dip in intensity at 588nm is characteristic of Helium, but other elements have their own characteristic energies at which they absorb photons. So if an atmosphere has a lot of Sodium in it, for example, that could also be detected through these characteristic dips in intensity. The ‘dips’ are usually very narrow indeed, as the absorption behaviour is generally sensitive to a very specific wavelength, hence they were soon informally called spectral lines. The first person to study this phenomenon was the German Astronomer Joseph Fraunhofer (1787 –
1826), after whom they are now more accurately named. These Fraunhofer lines had perplexed and amused astronomers across Europe since their discovery, but largely as a curiosity rather than anything else. Scientists began shining light through all known gases to examine the fingerprints they would leave, and cataloguing these patterns for posterity.

![Figure 8: Fraunhofer lines in a simulated spectrum.](image)

In fact, this was precisely what Norman Lockyer (1836 – 1920) saw and recorded in 1868 when he pointed his spectroscope at the Sun and measured a spectral line at 588nm. Yet the 588nm line had not been observed from any source on Earth, so clearly this was caused by some chemical hitherto unknown to science. And being a good classicist, Lockyer named the chemical Helium, after the Greek for ‘Sun’ (Helios). Though Lockyer took the naming rights, the French Astronomer Pierre Janssen (1824 – 1907) made the same discovery at almost exactly the same time, confirming Lockyer’s results.

Because of these vitally important Fraunhofer lines, Astronomers are able to look at the spectra of nearby stars and discover the chemical composition of their outer layers. We can even do this for planets, though obviously only by the light reflected from their parent star, so the measurement is significantly harder, but it has allowed us to determine for the first time what chemicals are present in the atmospheres of planets orbiting other stars.

This picture was intriguingly extended by the work of an Austrian physicist called Christian Doppler (1803 - 1853), who had been studying a phenomenon called binary stars. In these systems two stars orbit each other closely, often at very high speed. It had been known since antiquity that stars often have very different colours – a fact you can easily discern with the naked eye on a dark night. However, Doppler
noticed that in binary stars, quite often one star is measurably redder than the other. Doppler did some maths, based on a hunch, and worked out that an object moving sufficiently quickly towards the observer would emit light at a higher frequency (and hence bluer) than a stationary object. And an object moving away just as rapidly would emit redder light.

Doppler’s explanation was remarkably simple. Light, as you know, can behave either like a wave or a particle. In the case of the so-called Doppler effect, you can think of it as a wave. Now, imagine a wave as a sequence of peaks and troughs passing you at a certain speed (the speed of light, as it happens), and imagine what would happen if the object emitting those waves – let’s say a spaceship with a giant headlight – were to move towards you at high speed whilst continuing to emit exactly the same waves. If you sketch out the picture you may be able to convince yourself that the peaks and troughs of the wave would leave the spaceship slightly closer together because in the time between emitting one peak and the next one, the spaceship would have moved slightly forwards along with the light beam. So the new wavelength would be the old wavelength minus the distance that the spaceship could travel between one peak and the next. If the peaks are closer together, then that means that the wavelength is shorter, hence the light is bluer.

If the spaceship were instead moving away from you, then the wavelength you would measure would be longer, because between each new peak the spaceship would move a bit further away, so the effective wavelength would be the ‘resting’ wavelength, plus the distance the source travels backwards between pulses. Hence spaceships (or, indeed, anything) moving away from you sufficiently quickly should appear redder.

The so-called “Doppler effect” is of course familiar to you in the way that the pitch of an Ambulance siren rises as the Ambulance approaches and then drops as it speeds away. The speed of an ambulance (say 30
metres/second) is small in astronomical terms, but significant compared to the speed of sound (340 metres/second), so a significant difference in pitch can be heard.

![Diagram of the Doppler effect](image)

**Fig. 9:** The Doppler effect. As a source of waves moves at high speed, the distance between successive wave peaks decreases, and the pitch rises. In the opposite direction, the wavelength gets longer, so the pitch drops.

Well that’s all well and good, but in our example we could measure the wavelength of light emitted by the spaceship’s headlights at rest, so when we measured it when the spaceship was moving towards us, we could figure out the speed at which the spaceship was travelling in our direction based on the difference in wavelength. So we can only work out the speed of an object if we know what wavelength of light it would be emitting if it were at rest. And this is where Fraunhofer lines come in. You see, if a distant object is moving away from us at a high enough speed then the Fraunhofer absorption lines will appear at a longer wavelength than you would expect to find them. In fact, if you could look accurately enough at the Ambulance in the previous paragraph, you would notice that it changes colour as it whizzes past too. With the ambulance, the effect is miniscule because the Ambulance’s speed is tiny compared to the speed of light. However, for stars that might not be the case. If they moved at an appreciable fraction of the speed of light then we should definitely be able to measure this effect.
Doppler suggested that the effect he had discovered might explain a wide range of astronomical observations from the natural variability in star colours, to variable stars themselves. He was largely wrong, but his theory itself was correct, and only required a few tweaks by Einstein to account for Special Relativity.

Armed with this new knowledge, let’s turn back to Hubble and the second great experiment that he had just begun to undertake. Now thanks to the work of many astronomers of the 1920s, using Cepheid variable stars to measure distances, Hubble now knew the distance to a large number of nearby galaxies. However, that was only half of the puzzle. Next, he started measuring those galaxies’ relative velocities. The obvious place to start would be our large neighbour, the Andromeda Galaxy. Well it turns out that this giant sibling of ours is actually moving slowly towards the Milky Way – in fact, we now know that they two will collide in roughly 4 billion years, which should provide an impressive show for any of our descendants still alive at the time. However, as Hubble started looking at slightly more distant galaxies, something startling jumped out of the data – the more distant galaxies were all moving away from the Milky Way. And the further away they were, the faster they were receding.

This was truly extraordinary stuff. The Universe of the 1920s was assumed to be entirely stable, stationary and unchanging. Sure, if you looked at very close objects then they might be moving towards or away from us because of the unavoidable effects of gravity, but on sufficiently large scales the Universe was assumed to be entirely uniform and static. Hubble’s measurements were showing a very different picture – in fact, as the numbers came in, he realised that the overwhelming majority of galaxies are all moving away from us at extraordinary speeds. Does that mean that we hold a special place in the Universe after all? Nice try, but no – it turns out that wherever you stood in the Universe you would measure the same effect.
Imagine a lattice with galaxies at each point, and then imagine stretching the lattice – all points will move away from all other points, and the further apart two points begin, the further they will move apart.

**Fig. 10 : Universal expansion:** If you expand a lattice, then every single point on the lattice will appear to have moved further away from all other points, and points that started further apart will have moved apart even more than those that began closer together. This is what Hubble discovered for galaxies.

Hubble published this new discovery in 1929, and his observation that galaxies are moving away from us with a velocity proportional to their distance from us, is now known as *Hubble’s Law*. As it happens the idea had already been proposed a couple of years earlier by a Belgian priest called Georges Lemaître (1894 - 1966), though he had no proof of his speculation. The expanding Universe, it turns out, is a rather attractive idea to a priest because it implies that the Universe had a beginning. After all, it is expanding apart from *something* – if you reverse the expansion you get back to a point where the entire Universe was all located at one single point. Lemaître realised this, and proposed his hypothesis of the “primeval atom”. We now know it as the Big Bang, though I feel that modern physicists would say that Lemaître’s term is vastly closer to reality.
You see, there are two things you need to know about the Big Bang. Firstly, it wasn’t big – it was tiny. As tiny as it’s possible for anything to be, in fact. And secondly, it wasn’t a ‘bang’ because it didn’t make a noise, because there was nothing for it to make a noise in – there was no Universe yet. The term “Big Bang” was actually proposed as a joke, but as with many jokes, it stuck.

Anyway, the whole concept of the Universe beginning at a certain point in space and at a certain time is undeniably attractive to a priest because it suggests that there was a moment at which the Universe began, and therefore it seems more plausible to posit a creator. Indeed, in 1951, Pope Pius XII proclaimed that Lemaître’s theory provided at long last a rigorous basis on which to build a scientific theory of creation. Interestingly enough, Lemaître disagreed – he was deeply troubled by the idea of Creationism, and even managed to convince the Pope to stop meddling with science. Lemaître worked hard to reinforce the notion that Science and religion should be kept separate, writing shortly afterwards that

“...as far as I can see, such a theory remains entirely outside any metaphysical or religious question. It leaves the materialist free to deny any transcendent Being... For the believer, it removes any attempt at familiarity with God.”

Pius XII’s successor, Pope John XXIII, decided to follow this sage advice, and rewarded Lemaître with the honorific title of Monsignor in March 1960, appointing him president of the Pontifical Academy of Sciences ten days later. Just two years after Lemaître’s appointment, during the second Vatican council, the Roman Catholic Church finally began to make moves towards pardoning Galileo Galilei for his ‘heretical’ heliocentrism, eventually offering him a full posthumous pardon in 1992 under Pope John Paul II. The hand of Georges Lemaître certainly lay behind much of that progress.
Newton, however, was very much a construct of the 17th century in which he grew up. He had no time for those who denied the role of a creator God, writing in “A Short Schem of the True Religion” that “Atheism is so senseless and odious to mankind that it never had many professors.” I suspect he would be rather shocked by some of the professors he would meet today. Yet the concept of the Big Bang would have pleased him, it seems likely, as it allowed for a Universe that was created at a single point in time with all its laws already crystallised within its very structure.

Modern notions of the origin of our Universe are far more nuanced than those of Hubble and Lemaître. Physics as we know it breaks down and ceases to apply as we near the colossal temperatures and densities that existed in the early Universe. Even General Relativity, which predicts an infinitely dense ‘singularity’ at the beginning of the Universe, actually becomes unreliable near this point. New theories such as ‘loop quantum gravity’ or ‘string theory’ probe those first few moments, suggesting that perhaps the current Universe might be merely the most recent expanding epoch of a Universe that has existed for eternity into the past, and will exist for eternity into the future. Others suggest that the Universe comes and goes like a yo-yo, with infinite Universes stretching backwards and forwards in time, being born, expanding, dying and spawning child Universes over and over again. And then there are still those who, despite the warnings of Msgr. Lemaître can only see the Big Bang as cast-iron proof for a creator, despite the protestations of the entire cosmological community that it need not be the case. Cosmologists, though inquisitive and keen to find out more, are also perfectly happy to say “we don’t know”. That is enough for Science – indeed it is the only way in which Science can honestly respond to questions for which it doesn’t yet have an explanation.

It seems likely that Newton would have despised much of modern science because it removed, bit by bit, the role of a creator from the Universe. Yet here was a discovery that at least partly repaired the damage. On the other hand, the discoveries of Edwin Hubble showed us
our abject insignificance on the cosmic scale. The Universe most
definitely is not made for us – we are extremely recent arrivals on the
scene, inhabiting a wafer-thin layer around a small rocky planet,
orbiting a nondescript star, out in a modest spiral arm in an
unremarkable galaxy in one of many groups of galaxies in our local
cluster, which is one of countless other such galaxy clusters amongst
the billions of galaxies in the sky. The vast, overwhelming majority of
the Universe is not just unsuitable for life, but would be instantly fatal
to it.

In his legendary 1978 comedy radio play “The Hitchhiker’s Guide to
the Galaxy”, and subsequent novels in the same series, British
comedian and author Douglas Adams (1952 - 2001) wrote about the size
of the Universe and how we perceive it. The Guide has this to say about
space:

“Space,” it says, “is big. Really big. You just won't believe
how vastly, hugely, mind-bogglingly big it is. I mean, you
may think it's a long way down the road to the chemist's, but
that's just peanuts to space.”

Adams invents a torture machine called the “Total Perspective Vortex”,
in which a victim is forcefully exposed to the truly miniscule role that
they play in the Universe.

“The hopeless victims stand in the Vortex, and are suddenly
shown, for the merest instant, the whole of the Universe: the
whole infinity of creation, spanning over several trillion
light years, and countless millennia, with an insignificant
dot saying ‘You Are Here’”.

In Adams’s Universe, the sense of perspective that this provides
destroyes the victim’s mind. Perhaps I don’t have total perspective, or
perhaps I do and my mind has been destroyed. But either way, I rather
enjoy contemplating the size of the Universe and my own insignificance
in relation to it. I think that a sense of perspective is of inestimable value. In fact, I can’t think of many of the world’s problems that couldn’t be improved or solved entirely with a bit more humility. In one of the most beautiful ever pieces of science writing, the late great Astronomer Carl Sagan (1934 - 1996) describes a photograph taken by the Voyager 1 spacecraft in 1990 as it turned its primary camera back towards home. In that grainy scene, if you squint carefully, you can just pick out a pale blue dot, barely visible against the blackness of space.

“From this distant vantage point, the Earth might not seem of any particular interest. But for us, it’s different. Consider again that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every ‘superstar,’ every ‘supreme leader,’ every saint and sinner in the history of our species lived there – on a mote of dust suspended in a sunbeam.”

Sagan is the one name towards which all science communicators aspire because he so beautifully and simply captured the sense of wonder and amazement that Astronomy, like all sciences, should engender in the human mind. The cosmology that Hubble began has continued to demonstrate our insignificance compared with the vastness of the cosmos, but by doing so it has brought a sense of perspective that, pace Douglas Adams, can only be a good thing for humanity.
Man as Machine

"I can calculate the motions of the heavenly bodies, but not the madness of people."
Newton

Dr James Hiram Bedford was an unlikely pioneer – a gentle, quiet professor of psychology who specialised in vocational training and career counselling. He authored six books on his area of professional expertise, and was a keen traveller, having been on safari in Africa, as well as travelling extensively around Europe and Canada. He had been married twice, his first wife Anna tragically dying in 1917 only months after their wedding day. He married again three years later to his second wife, Rudy, and the relationship was a happy one. They started a family together, eventually raising five children and living a full and successful life. Dr Bedford finally passed away at 1:15pm on Thursday 12th January, 1967. He died of cardiorespiratory arrest triggered by advanced kidney cancer which had metastasized to his lungs.

James H. Bedford was 73 years old when he died, and if all goes according to plan he will come back to life at some point in a few centuries’ time and he will never die again. You see, Dr Bedford’s death was not tremendously unusual, but what happened immediately afterwards was to make history.

Almost as soon as Dr Bedford died, a legion of doctors sprang into action, following a long-rehearsed plan. His body was encased in ice, and a man called Robert Nelson was immediately summoned to oversee a carefully choreographed medical procedure. Mr Nelson was head of
the Cryonics Society of California, an organisation dedicated to extending human life after death by freezing the human body down to intensely cold temperatures, using a combination of industrial chemicals and cutting-edge medical technology. Bedford was the first ever human being to subject himself to this procedure, having been sponsored through this process by the Life Extension Society – one of the world’s first ever cryonics organisations. And Bedford’s case made headlines, albeit not for the right reasons. Shortly after the freezing process was begun, it was discovered that Robert Nelson’s team had botched the job so completely that they were removed from the case, and Bedford’s frozen body was transferred immediately to the rather more competent Cryo-Care Equipment Corporation in Phoenix, Arizona.

Nelson’s methods had been crude – he pumped Bedford’s body full of dimethyl sulfoxide – an anti-freeze or cryoprotectant. Then he packed the body in slabs of dry ice (frozen carbon dioxide at roughly eighty degrees below zero Centigrade). Once at Cryo-Care, Bedford was sealed into a thermally controlled dewar full of liquid nitrogen, where his body was lowered to the storage temperature of -196°C. Despite being shifted around between various facilities, Dr Bedford has remained frozen since the day of his death, and an examination of his body in 1991 revealed it still to be in good condition.

Well, as good as could be expected, given the circumstances…

Despite Dr Bedford’s extraordinary tale it seems to me highly unlikely that he will ever be reincarnated, though given the stories that we have encountered so far I’m reluctant to speculate about the advances that science might make in future decades. Whenever someone claims that science can’t do a thing, it usually surpasses all expectations.

The main worry in Dr Bedford’s case is that the brain would have suffered so much damage immediately after death and during the freezing process, that it would be impossible to restore it to its previous
condition. Yet if it were possible, what an extraordinary world Dr Bedford would awake to – a world surpassing our wildest futurist fantasies. In the blink of an eye, everyone he ever knew would be dead – his family, his friends, the film stars and musicians that he enjoyed. Since Bedford’s death we have already witnessed a great many changes - the cold war has ended, computers and the Internet have appeared from nowhere and now pervade our lives, and with a bit of luck we will soon all have the rocket-powered jetpacks that we’ve been promised for so long. Who knows what other technologies might be available to those able to master the secret of reanimation?

James Hiram Bedford currently rests in the facilities of the Alcor Life Extension Foundation in Scottsdale, Arizona. These days there are over one hundred other patients to keep him company in his slumber, together with several dozen pets. Many of the other people frozen by the Cryonics Society of California were not so lucky – Bedford was the only one of the first batch not to have been allowed to thaw out at some point in his tenure. As you can imagine, numerous bizarre lawsuits ensued.

Yet even in the midst of this extraordinary modern technology, it’s surprising how little has changed in four thousand years. The practice of cryogenically freezing the human body shortly after death is merely a 21st Century version of the art of mummification, by which the Ancient Egyptians, and several other ancient cultures, prepared the bodies of their dead for the afterlife. Egyptians, both rich and poor, believed that their bodies would rise again, not on this Earth, but in the world beyond. And they, too, were often buried with their pets, and sometimes their servants too (willingly or otherwise). The only major difference was that Egyptians were also often buried with Earthly goods that they would require in the afterlife, whereas at least those who are cryogenically frozen today are aware that the world to which they hope to awake will be the same physical space in which they died. Albeit substantially changed by technological advances, of course.
Well, that’s not the only difference. Perhaps one of the most significant changes between cryogenic freezing and the Egyptian mummification process was that the Egyptians didn’t preserve the entire body; they got rid of all the unnecessary internal organs, storing only the most important ones that would be needed in the afterlife – the lungs, heart, liver and intestines. These were carefully removed and kept in special vessels, called Canopic jars, often decorated with ornate heads, representing the sons of the god Horus – a human, a baboon, a jackal and a falcon. This process continued up until around the 6th or 5th century BC, after which time the organs were increasingly buried inside or alongside the body instead.

But you might be wondering precisely what the Egyptians did with the brain. After all, this is undoubtedly the most important organ in the human body, the source of our intellect, our wisdom, our personality and memories. Everything that makes us human is contained in that ornately folded mass of jelly-like tissue. So what did the Egyptians do during the mummification process to preserve this most vital of organs? Simple - they wrenched it out through the nasal cavity with a metal hook, and threw it away. The brain, to the Egyptians, was an unremarkable and unimportant organ and just got in the way of the mummification ceremony. The empty skull cavity was washed out with spiced liquid, and the process continued minus the only organ that matters. The Egyptians, like many before and after them, believed that the heart was the seat of the human soul – they thought that the heart was the place where human passions, perception and intellect were based. The brain was just padding.

You can hardly blame them, I suppose. Understanding of human anatomy was patchy at best in the ancient world. The Greeks briefly flirted with the idea that the brain might be the source of human intelligence, but then Aristotle – whose scientific ideas dominated Western thought for two millennia – decided that the brain was little more than an elaborate radiator, and that the heart was the origin of our
personality. The celebrated Roman physician Galen\textsuperscript{76} was known to dissect cadavers of human beings and animals (both living and dead) and discovered that the brain controls at least some of the body’s muscle groups. But that was about as far as he got with it.

Precious little happened then for rather a long time, until the 16\textsuperscript{th} century. In fact, almost exactly one hundred years before Newton was born, the Belgian physician Andreas Vesalius (1514 – 1564) published his celebrated work on human anatomy, \textit{De humani corporis fabrica}, or “On the structure of the human body”. This was a highly influential and financially lucrative publication, which covered the results of a lifetime of knowledge gleaned from human dissections tightly packed into seven lavishly illustrated volumes.

Vesalius was one of the first people to investigate the human nervous system in painstaking detail, and to extend Galen’s work on the role of the brain in the management of the various muscles which power the human body. He identified the role of nerves in transmitting signals to and from the muscles, and showed that nerves originate in the brain, not the heart. The heart, he demonstrated, was not the seat of intellect, but rather just a device for pumping blood through our arteries and veins.

By the time Newton reached University, Vesalius’s work was widespread and celebrated throughout the foremost places of learning in Europe. Though his discoveries were not revolutionary, in the sense that Newton’s would prove to be a few years later, Vesalius triggered a renaissance in the study of the human body as a biological curiosity rather than a sacred and untouchable spirit vessel.

Much work was done in the 16\textsuperscript{th} and 17\textsuperscript{th} centuries on brain anatomy, with use of the increasingly fine microscopes now available to wealthy European scientists in order to examine not just the macroscopic structure of the brain, but also its microscopic properties. Yet even by the 19\textsuperscript{th} Century the field still left a lot to be desired. Thomas Edison,

\textsuperscript{76} Born Claudius Galenus, 129CE
for example – and I promise that this is real – thought that the brain contained “little peoples” under the control of “master entities” who “live in the field of Broca”. He believed that these tiny workers were literally responsible for operating the entire human mind.

“There may be twelve or fifteen shifts that change about and are on duty at different times like men in a factory....Therefore it seems likely that remembering a thing is a matter of getting in touch with the shift that was on duty when the recording was done.”

It isn’t immediately obvious whether or not Edison was joking. Yet at least it suffices to show that the study of the brain still left a lot to be desired. Until the 19th Century, that is, when the field exploded with a wealth of new discoveries covering all aspects of neural anatomy, and an intriguing new field called “Psychology”.

Strictly speaking, of course, Psychology wasn’t an entirely new discipline, given that the functioning of the human mind had always been of interest to philosophers through the ages – but the fervour of scientific activity of the 19th Century triggered a new wave of interest, and this time it came backed by a better understanding of experimental method and anatomical models for brain function. By the latter part of the 19th Century this new movement really began to come into its own, with the work of the celebrated Austrian psychoanalyst Sigmund Freud (1856 – 1939).

Freud’s name is well-known even today, though his contribution to modern psychoanalysis is perhaps rather muted. Many of his ideas have been largely rejected and his methods have been heavily criticised. Freud, it is said, had a demonstrable eagerness to leap to unjustified conclusions when analysing his patients, especially in his Interpretation of Dreams – a work which is almost completely rejected by modern

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scholarship. Yet the specific theories that Freud put forward were perhaps less important than the processes he developed, treating neurological conditions through *conversation* rather than surgery.

One of Freud’s most significant ideas was the separation of the human mind into three separate components, each fulfilling different roles and possessing different strengths and weaknesses. The *Id* is the primal, emotional, passionate part of our brain – the source of our sexual urges, fears and desires. The *Ego* is more of a ‘human’ component, directing our impulses in a way that takes into account present and future repercussions of our actions, and imposing reason on our animal desires. And thirdly, there is the *Super-Ego*, which is the ‘modern’ part of our brain comprising the learned cultural norms and expectations, together with the sense of conscience that generates guilt and regret.

Freud’s theory was not directly linked to any specific features in the brain itself, but rather he was trying to come up with a picture that explained the way that human minds *appeared* to work from the outside. However, the model he designed was certainly influenced by evolutionary thinking and studies of nonhuman primates, where it was abundantly clear that our human brain is merely a modern refinement of an ancient and widespread device. The human brain is the product of a great many millions of years of evolution, gradually extending the organ which we inherited from our early mammalian ancestors, but leaving many significant elements very much intact. Though our brains contain some powerful modern adaptations, they are still built upon some alarmingly primitive core components.

Freud’s work on the mind was the culmination of his career, published in the early 1920s as Hubble was discovering the vastness of the Universe and Schrödinger was putting together his revolutionary thoughts on Quantum Theory. Freud’s earlier work is perhaps more familiar, dealing to a great extent with the conflict (as he would later term it) between the *Id* and the *Super-Ego*. Much of his writing focussed on repressed sexual urges, most memorably that between a
child and its parents. Having spent many years treating patients who had suffered from sexual abuse in their childhood years, Freud became obsessed with the concept of repressed sexual urges motivating much of human behaviour, largely through the action of the unconscious mind. His techniques were designed to prise out such feelings from under the weight of repression, to bring them into the open and to deal with them directly. The aim being that, by so doing, the therapist might help the patient to deal with whatever consequent problems they had been suffering.

Given his history of hands-on research into mental illness and neuropathology, Freud’s later life swerved sharply away from the more brutal medical techniques that others were using at the time. It is certain that the overly scalpel-heavy neurological medicine of the late 19th and early 20th centuries did a great deal of harm, probably more harm than good in fact. Yet Freud’s perspective was perhaps too extreme in the opposite direction – especially his incessant fascination with unconscious sexual desire, which seems, at least according to modern thought on the matter, to have said a great deal more about him than about any of his patients.

Freud’s theory was bold because it competed against an established mode of thought that saw brain problems as being no different to liver problems or heart problems. Psychological issues were merely macroscopic brain defects that could be studied and fixed, usually by the use of alarmingly sizeable knives. For much of the early 19th Century, roughly up to Freud’s birth, study of the human brain had been heavily influenced by a claim now considered a fringe pseudoscience, but which was at the time an extremely fashionable belief. The study of phrenology was initially developed at the very end of the 18th Century by the German physician Franz Joseph Gall (1758 – 1828), yet it persisted well into the 1800s with a few modifications to make it more easily marketable. The fundamental idea behind this whole concept was that specific parts of the brain were responsible for certain aspects of a human being’s personality. Moreover, the size and shape of these
regions of the brain not only provided information about these aspects of personality on dissection, but could actually be measured in a living patient by examining the shape of the human skull.

Perhaps this would be a good time to discuss pseudoscience, and phrenology is as good an example as any. The origins of this bizarre belief system certainly supply us with a great deal of information about how utterly unfounded claims become accepted and even propagated by people who should know better. The term ‘pseudoscience’ means ‘something which pretends to be a science, but isn’t’. In other words, it’s nonsense wrapped in the external plausibility of scientific terminology.

There are many good ways to tell a pseudoscience from an actual scientific discipline, and it’s definitely worth going through these so that you can be armed with the toolkit to spot nonsense at a hundred paces. As you might have guessed, the modern world is awash with pseudoscience in practically every aspect of our lives. Learning to recognise it not only saves you a lot of time, effort and money, but might also keep you healthier, happier and more successful too.

So before we talk about pseudoscience, this might actually be a good opportunity to remind ourselves what science actually is.

Science is the process that we human beings have developed, and are continuing to perfect, by which we can discover answers to questions concerning the physical Universe. Science does this in a way that reliably gets us as close as possible to the truth. Moreover, it tells us the confidence with which we can hold the answers we obtain, and the kind of evidence we should require to change our minds.

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78 This is my definition. Others disagree, or put emphasis elsewhere. To me, this is the fundamental description of the most important features of the scientific discipline – most of the rest is just detail.
Science is a process for learning – though it’s the best process we have. Its sole purpose is to place claims on a spectrum of certainty, from true to false, and to know how those claims should be moved around on that scale as and when new evidence appears. So if anyone claims that they have learned something new and important but they have used a process wildly different to that which history has shown to be the most accurate, it should certainly raise a few eyebrows from those with any interest in learning the truth and avoiding delusion.

Actually, it’s remarkable how many aspects of the story of phrenology are still seen in the pseudosciences of today. Pseudosciences often build up around a single individual. In the case of phrenology, Franz Gall was rejected by the scientific communities of several countries, especially his native Austria as well as the French republic under Napoleon Bonaparte. Apparently undeterred by their rejection of his ‘discovery’, and unperturbed by their criticism of his theory for lacking supporting evidence, Gall continued to spread his ideas, eventually winning a following of sorts in Paris, and some intellectual acceptance in Britain and the US. Without such a charismatic leader, it is unlikely that phrenology would have survived for long.

Pseudosciences usually seem *superficially* plausible. Phrenology was built on the assumption that the size of an organ or, in this case, the size of certain bits of the brain, increases in proportion to their workload. This does not seem unreasonable – after all, if we lift heavy weights at the gym, we repeatedly exercise certain muscle groups which then grow to unnaturally large sizes. In fact, to some extent this actually turns out to be true in the brain as well. Not only that, but another of the fundamental underlying assumptions of phrenology – namely that the brain is divided into regions each with its own specialised function, also turns out to be partly correct. But whereas many of the assumptions of phrenology are plausible, it just takes one to be false to sink the whole claim – in this case, it just isn’t true that crude measurements of the skull can tell us anything generally useful about the personality of the person inside it.
But this minor triviality didn’t stop the phrenologists. In fact, they took everything a step further – they claimed that not only could a human being’s intellect or aggression level be determined using these methods, but even more subtle personality traits could be ascertained by a suitably skilled practitioner. Indeed, in the early 1800s, employers often asked job applicants for phrenology reports to make sure that their new recruits would be suitable employees.

Preposterous, you say, and I quite agree. It’s utterly ridiculous for a so-called advanced society to require employees to submit to pseudoscientific and demonstrably worthless testing in order to determine whether they are hard-working, honest and dependable. In fact, such testing, given that it could not possibly have accurately ascertained that which it pretended to determine, was blatantly just a way to amplify the underlying prejudices and biases of the employers themselves. But, of course, that was the early nineteenth century, and this is the 21st. We all know that doesn’t happen now, right?

Well, no. As you might have guessed, this sort of nonsense is still going on to a very great degree across the world, even in its most prosperous and well-educated countries. For example, in Japan many companies demand knowledge of the blood type of potential employees before they are hired, in the completely false and unfounded belief that this is in some way correlated with an employee’s personality. When the scandal-struck Minister for Reconstruction, Ryu Matsumoto, resigned in the summer of 2011, he blamed his blood type (“B”, apparently) for the offensive remarks that ended his career. Some Japanese companies are reputed to fill entire divisions uniquely with people of the same blood type in the belief that they would perform better than another group selected at random from equally qualified applicants. Needless to say, there isn’t a shred of evidence to support any of this.

Superstitious employers both in the Western and Eastern countries have been known to consult horoscopes before making hires, and a quick
web search now informs me that every employment agency in the first page of search results offers horoscopes to their clients. Scorpios, I am told, are inquisitive and analytical, and include such strikingly similar, likeminded personalities as Bill Gates, Pablo Picasso and Whoopi Goldberg.

The one thing that such pseudosciences all have in common is that a relatively simple double-blind study would immediately disprove any claim they make, but yet their proponents are either passionately opposed to doing such a study, or angrily dismissive of any such studies that obtain the predictable negative results. Again, the pattern is so familiar to those of us who have studied the field for any length of time that you can practically set your watch on it. First, the pseudoscientist claims that science backs up their claim. Then a real scientist will conduct a study showing the claim to be false. Then the pseudoscientist will claim that the scientist is either (a) incompetent to conduct the test, (b) narrow minded, (c) in the pocket of whichever organisation the pseudoscientist opposes, or (d) part of a global conspiracy to cover up their new discovery.

When proper scientists investigate and disprove elements of a pseudoscience, the proponents rarely abandon their position, but either retreat into denial, or start making up entirely fictional claims to rescue their beliefs – a technique known as special pleading. When their claims are under attack, and the opposition seems overwhelming, the defenders of pseudoscience usually pull out the good-old “Galileo gambit”, which runs something like this:

“You may well laugh at our theory, but the establishment persecuted Galileo, and in the end he was vindicated and revered for his work!”

The implication, obviously, is that the pseudoscientist’s theory will also be vindicated in time. Of course, a very great many upstart theories are rejected, and almost all of them stay rejected, and rightfully so –
because they are completely wrong. Galileo was a very rare exception, and he lived well before the scientific community, together with its rigorous standards of peer review, was founded. What Galileo was rebelling against was not, in any sense, a scientific consensus.

Though the practice of phrenology had greatly reduced by the beginning of the 20th century, the humourist Ambrose Bierce in his 1911 work “The Devil’s Dictionary” still felt that it merited a particularly scathing entry:

“Phrenology: The science of picking the pocket through the scalp. It consists in locating and exploiting the organ that one is a dupe with.”

Phrenology eventually died out, yet plenty of pseudoscientific beliefs from that same period still survive. Perhaps the most bizarre of these is the pseudoscience of homeopathy, which we briefly met in the chapter on germ theory. Homeopathy was a kind of early-19th century magic-potion cult decorated with a hint of alchemical ritual. Despite the fact that it was based around principles that were even less plausible than those of phrenology, it still exists today, much to the utter bewilderment of anyone with any grounding in rational scientific thought. If you examine the arguments given by homeopaths in the 21st Century you will see that they neatly follow the exact same path that the phrenologists followed, and that pseudosciences have always followed through the ages. The only two new additions to the debate seem to be the more recent tactics of (1) associating your pseudoscience with theoretical physics – usually quantum mechanics – to try to confuse the public into believing it, and (2) the familiar retort “there may be no evidence it works, but what’s the harm?”, as if spreading false hope and misinformation, discrediting the scientific consensus and selling worthless nonsense to the public are not sufficiently damaging and morally repugnant in and of themselves.

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Pseudosciences, as I have said, are often built around a kernel of truth. This makes them much better at overcoming the initial scepticism with which novel ideas are often greeted. In the example of phrenology, that kernel of truth was the correct assertion that the brain is not one big homogeneous blob, but rather that different parts of it seem to be specialised towards certain functions. And that particular claim was most famously and most spectacularly demonstrated in the tragic story of a young American man who suffered perhaps one of the most extraordinary work-related-injuries ever recorded in human history, in a remarkable case that triggered a newfound surge of interest in brain anatomy.

In 1848, Phineas Gage was a 25 year old railroad worker, based in Vermont in the North-Eastern United States. He worked with a team which had been given the important task of forcing a route through difficult, hilly terrain. They did this by drilling holes in the bedrock, filling them with explosives and blasting the rock apart, then removing the resultant pile of rubble by hand. It was exhausting and extremely dangerous work. Once the holes were drilled, the most perilous part of the job was in actually preparing the explosive charge within. To do this, a quantity of gunpowder was poured into the hole, and then compacted together with a fuse, often using a hefty metal bar or tamping iron. On 23rd September 1848, this was Gage’s job, and he was using his own tamping iron for the purpose – a hefty shaft of solid iron over a metre long and six kilogrammes in weight.

Gage was young, but highly experienced at this job. He had done exactly this same procedure many times before, carefully preparing the fuse, and then tamping down the powder into the hole so that it would detonate correctly and shift as much rock as possible. But on this fateful day, something went wrong that would change his life forever. From eyewitness reports we can piece together a rough impression of events that followed, and it paints a thoroughly gruesome picture. As Gage was tamping down the charge, his tamping iron caught the rock at an
unfortunate angle, which produced a spark right above the gunpowder. The powder ignited, detonating violently in an explosion that propelled Gage’s weighty tamping iron with destructive force directly upwards, through Gage’s lower jaw, up into his skull, through the front left portion of his brain, and splintering out from the top of his skull, all in a blinding flash and a cloud of debris.

According to an official medical report on the accident by John M Harlow, published the same year in the Bulletin of the Massachusetts Medical Society, such was the force of the blast that Gage’s lifeless body was hurled many metres backwards. The tamping iron itself exited through his skull, and was found roughly 25 metres away, smeared with blood and brain.

The most miraculous fact about Gage’s story – and the only reason that I allowed myself the luxury of adding those fabulously gory details – was that Gage somehow survived the accident. In fact, not only did he survive, but shortly afterwards, when his friends ran over expecting to find him dead, they were surprised to discover that he was very much alive, conscious (albeit shocked) and able to hold an intelligible conversation with ease despite missing a large chunk of his head. The report of the attending physicians reads like a cheap horror film, describing Gage’s pulsating brain, bits of which literally fell out as he was being examined.

For ten days, Gage remained in intensive medical care, the substantial blood loss seeming to cause more issues than the large fraction of his head that was missing. Then on 23rd September, he began to pass into a comatose state, seemingly nearing death. But yet again, death didn’t arrive, and Gage eventually recovered once more, holding conversations with his friends, walking around the hospital, and seemingly keen to return to the outside world. Two months later, Gage returned home, and then apparently embarked on the life of a minor celebrity for a while as “the man with a hole through his head”. Yet despite the fact that Gage physically survived the horrific accident, all
was not right with him. He displayed some visible paralysis in his face, lost the sight in his left eye, and began to suffer from epileptic seizures. But there was more than that – psychologically, Gage wasn’t quite the man he used to be.

Recent studies claim that perhaps the extent of Gage’s personality changes have been greatly exaggerated, but even the more cautious reading of the facts paints a picture of a respectable, hard-working man who turned almost literally overnight into a rude, impatient, lazy and inconsiderate layabout. Gage never returned to his old job, though he went on to live for another twelve years after his accident, eventually dying of a severe epileptic convulsion. Gage’s skull (and his infamous tamping iron) are now on display in the Warren Anatomical Museum in Boston, Massachusetts, US and they stand as evidence for one of the most extraordinary medical cases ever known.

Though Gage’s injury had bypassed the central regions of his brain – the bits that govern memory, emotion, vital bodily functions and senses – they had seriously damaged the frontal lobes on his left side, and this is the part of the brain that, more than any other region, sets us as human beings apart from the rest of the animal kingdom. It’s not that the brains of other animals don’t have these features, it’s just that the frontal lobes of human beings are considerably more developed than those in any other animal species on Earth.

In fact, the frontal lobes, as was discovered in Gage’s case and in many other similar cases since then, are largely involved in what Freud would have termed the Ego – the part of our brain that controls the impulses and primitive desires that the rest of the brain is generating in response to stimuli from the outside world. Damage to the frontal lobes can make it harder, or even impossible, to focus on specific tasks, it can increase irritability, cause loss of impulse control, inability to plan towards goals, inability to anticipate and respond to the actions of others, increased risk taking and many other effects. In short, by damaging a physical part of the human brain, you can very substantially
change a human being’s personality. The part of us that we consider to be most special, uniquely us, is just the result of physical processes taking place in the cells of our brain.

Even today, this hypothesis is still rather controversial outside of scientific circles. Of course, there is no doubt amongst neuroscientists who have actually studied the effects of brain damage scientifically, but amongst non-experts this new understanding has been slow to take hold because it goes against so much that we feel and want to be true. For all of recorded human history the brain and the mind were assumed to be separate things – the brain being a physical organ in the skull, and the mind being some external property of a human being, somehow linked to the actions of the brain, but not completely determined by it. Celebrated French philosopher René Descartes (1596 – 1650) wrote in his *Meditations on First Philosophy* (1641) that the mind and body were two separate entities, with the brain providing intelligence, memory and language, but the mind, which he imagined to be some sort of non-physical entity external to the body, providing self-awareness and consciousness. Even today the concept of consciousness provides ample fodder for armchair philosophers, and many don’t feel ready to abandon Descartes’ dualism entirely.

As part of his thesis, Descartes postulated that mind and body were constructed from two different types of matter. The brain and the rest of the body were material – that is, flesh and blood. Material things can be touched, pushed, picked up, prodded and probed. But they cannot think, they cannot experience. On the other hand the mind was made of different stuff; some sort of mental substance that does not have physical properties. The mind cannot be touched or measured, but it can interact with the body in some sense, and it does have the capacity to think, to contemplate, to experience the world in all its glory. According to Descartes, and for reasons that I cannot fathom, he decided that the interaction between these two distinct entities took

79 How, one wonders, if it is not formed from a physical substance? Isn’t “the ability to interact physically with matter” a definitive property of material substances?

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place in the pineal gland – a small organ towards the base of the brain which, as we now know, actually seems to be involved in regulation of the body’s internal clock.

Of course there is no evidence whatsoever that Descartes’ idea is correct, and building a model for how this situation might even work is extremely problematic. Yet the concept of consciousness is such a powerful illusion, and the assumption of an immaterial ‘soul’ or ‘mind’ is such a natural solution to that problem, that it seems to be a common feature across all human cultures, in history and today, from the modernised Western world to tribes hidden deep in the Amazon rainforest or the jungles of Sumatra.

The picture is shifting gradually, however. Over the last two centuries, this fundamental distinction between brain and mind has gradually begun to dissolve, starting in part with analysis of cases such as that of Phineas Gage, which demonstrate that physical damage to the brain can cause changes in personality, character and behaviour that were previously thought to be the domain of the non-corporeal mind. The view of most modern philosophers and pretty much all neuroscientists is that the mind – consciousness – is an illusion constructed by the (purely physical) brain in order to make sense of a series of stimuli that occur in temporal sequence.

What is clear from neuroscience is that the brain is constantly building up and updating its own internal story to explain what it perceives in the world around. It does this based on stimuli from the eyes, ears, sense of touch and other senses, all of which arrive at differing times, with different brain systems processing them at different speeds. Yet the brain conjures up a picture that makes sense of all these stimuli in a coherent but utterly artificial internal narrative.

A fascinating series of studies\textsuperscript{80} that took place in the 1980s gave us an enticing new understanding of how exactly the brain and mind are

\textsuperscript{80} Libet et al., Brain (Oxford University Press), 1983

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connected – and as suspected it turns out that the brain is the only player in the game. Benjamin Libet (1916 – 2007) set up an ingenious series of experiments in which human subjects were asked to sit before a simple apparatus consisting of a single push-button, whilst being hooked up to an ElectroEncephaloGram (EEG) device which monitored their brain activity. The subjects were asked to press the button whenever they wished, then note the time at which they consciously decided to act by watching the position of a moving dot on a screen in front of them. There would be some delay between consciously deciding to act, and the actual neural signals triggering the muscular response, but that wasn’t what this experiment was designed to investigate. Instead, Libet’s study showed something that would spark a revolution in the understanding of consciousness: the EEG readings showed conclusively that the subjects made a decision to act well before the button was pressed, but more importantly, well before they were even aware that they had made the decision. I say “well before”, but it was approximately 50 milliseconds, or 1/20th of a second. Still, it was a significant gap – after all, light can travel 15,000 kilometres in that time…

A number of other similar experiments immediately followed this extraordinary result, including, in 2008, a group of researchers from the Max Planck Institute for Computational Neuroscience in Berlin. The results of their study81 showed that they could predict which hand a subject would use to press a switch up to seven seconds before the subject believed they had made the conscious decision. Clearly consciousness of a decision follows the actual neurological decision to act, it does not precede it. Therefore the conscious mind cannot possibly be controlling the brain – the brain and the mind are the same thing and consciousness is merely an illusion that the brain fabricates in order to tie together all the stimuli that it has processed.

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81 Haynes et al., Nature Neuroscience, April 13th 2008
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In modern times, the invention of the MRI scanner, PET scanner and EEG devices\(^{82}\) have so transformed the field of neuroscience that they have literally allowed us to watch a living human brain in the process of thinking, revealing the very structure of thought. Yet for most of the history of neuroscience, we were forced to study the unfortunate few like Phineas Gage – examining what happens to a human mind when the brain has been damaged by physical trauma, illness or age-related degeneration. The modern functional map of the brain, which allows us to pinpoint exactly which parts are responsible for language, sight, hearing and so on, was largely determined by examining which faculty was lost when each part was damaged.

One of the most profound areas of research nowadays concerns mental illness and the relation between specific physical pathologies and external behavioural patterns. Mental illness had been a primarily religious question for many centuries, especially in Europe where diseases such as epilepsy manifested the sort of symptoms that medieval superstitions assumed could only come from demonic possession. Hippocrates (c 460 BCE – c 370 BCE) actually wrote of the illness on or around 400 BC in his work “On the Sacred Disease”. Perhaps surprisingly, Hippocrates actually assigned purely physical causes to this debilitating condition, instead of agreeing with the prevailing thought of the time that such convulsions could only possibly be caused by divine interference.

> “Men being in want of the means of life, invent many and various things, and devise many contrivances for all other things and for this disease, ... assigning the cause to a god.”

Prior theories were almost entirely supernatural. The Babylonians believed that epilepsy was caused by demons which possessed the

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\(^{82}\) These are all devices that allow higher resolution (spatially or temporally) monitoring of the activity of the brain. If you genuinely care what the acronyms stand for then please look them up but… well… they use the acronyms for a reason 😊 258
fathers of epileptic children in the case that they had sex too soon after urinating. Jewish thought (and later, Christian teaching) ascribed epilepsy to evil demons. Yet Hippocrates’ view was that it is ridiculous to imagine the impure human body could ever be polluted by the most holy of sources. So Hippocrates discarded the divine origin of epilepsy, though perhaps for reasons that we might today regard as less than rigorous. The analysis that follows is at least admirable in its rigour for the time, though by modern measures it doesn’t come close to fitting in with the established models of human anatomy today. Hippocrates draws on the theory of the four humours, which assigned bodily disease to the imbalance of four substances of which it was supposedly composed. In epileptics, so Hippocrates’ theory goes, the familiar neurological symptoms are caused by a build-up of phlegm in the brain which is unable to drain away sufficiently quickly.

As time progresses, as is sadly true with much of science, understanding actually reversed – at least in the Western world. After the Greek civilisation began to fall, so with it went the culture of open learning that so characterised the achievements of Socrates, Plato, Aristotle and Hippocrates. The Roman Empire, though remarkable in so many ways, had a less civilised view of pure thought. Hippocrates’ theory was just that – a theory without any solid experimental evidence, so it didn’t take much to topple it, and the official story soon reverted to the unfortunate superstitious belief that epilepsy was evidence of supernatural interference.

The fall of the Western Roman Empire marks the beginning of a millennium of superstition and scientific retardation that we, as a species, are lucky to have escaped. During this period in Europe, religious teaching focused on epilepsy as evidence of demonic possession, partly due to several verses in the New Testament that describe Jesus and his disciples casting ‘demons’ out of people they met – people who convulsed in ways that sound eerily familiar to modern ears.
Indeed, that medieval viewpoint isn’t entirely dead, even today. A 2003 survey by the National Society for Epilepsy found that, even in modern-day London, 5% of people surveyed thought that evil spirits were to blame for epilepsy. A 2005 study\(^83\) of Malaysian University students found that 5.3% thought evil spirits were to blame, and 4.9% thought it was contagious. The problem is particularly bad in those areas with deeply entrenched traditional religious beliefs and very poor access to education and medical advice. In much of sub-Saharan Africa, cultural beliefs that epilepsy is caused by witchcraft, evil spirits and magic curses are difficult to overturn. The World Health Organisation estimates\(^84\) that 80% of people suffering from epilepsy around the world are to be found in developing nations and in many cases sufferers are reluctant to seek treatment from Western medicine partly because they believe that the condition has supernatural origins that medicine cannot treat\(^85\). Even in the 21\(^{st}\) Century, the Roman Catholic Church has an official *Rite of Exorcism*, which it helpfully revised in 1999 with the added guidelines that *most* reported cases of possession can, in fact, be ascribed to mental illness. Not *all* of them, of course…

Epilepsy is one neurological condition that has very vivid and memorable symptoms, and consequently it is one that has inspired particularly drastic and far-fetched explanations. But the most profound change in the area of psychological wellbeing may well have begun when modern neuroscientists started working on the neurological basis of common character traits. How does the physical structure of an individual’s brain determine the way that they behave in their everyday life? We have met Phineas Gage and the way that damage to his frontal lobes caused him to change in personality, but what else could we discover? We know, for example, that skills such as language acquisition are governed by specific areas of the brain, and that they can

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\(^{84}\) WHO (2004), *Epilepsy in the WHO Africa Region, Bridging the gap: the global campaign against epilepsy*, WHO Press, Geneva  
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be seriously adversely affected by trauma or genetic diseases that strike that very location. Could human beings, through some kind of impairment to parts of the brain concerned with social interaction, for example, become far more anti-social than their peers? As with most stories, at this point we inevitably find ourselves back at the door of Isaac Newton.

Newton was a lonely type, often spending days on end without emerging from his rooms, working through the night on a task that had suddenly occupied his mind to the extent that he would even forget to eat meals. The level of focus that he displayed was almost certainly vital for his work, and one might argue that a more easily distracted version of Isaac Newton – one with a taste for socialising, or a strong interest in sex and drink, say – may not have discovered such a quantity or profundity of novel scientific theories. There are those who claim that Newton’s famous isolationism, single-mindedness and social awkwardness may well point to a diagnosis of Asperger syndrome. This condition, which almost exclusively affects males, and which is believed to be largely genetic, is nowadays considered just part of the autistic spectrum rather than a separate condition, lying somewhere in the middle of the severity scale. Children with Asperger syndrome usually have difficulty in social situations (check!), restricted interests, often with an intense focus on specific subjects (check!), a lack of empathy often leading to difficulties maintaining friendships or personal relationships (check!), occasional susceptibility to talking at length without care for the interests of the listeners (check!, according to accounts of Newton’s lecturing habits), and a peculiar or entirely lacking sense of humour (check!).

Some prominent modern researchers, including leading Autism expert Simon Baron-Cohen, director of the Autism Research Centre at Cambridge University, have proposed a framework for understanding autistic spectrum disorders such as Asperger syndrome, as being
evidence of an “extreme male brain”. Typically, male children exhibit stronger inclination towards systemizing (that is, organising objects into groups, spotting patterns, deducing logical relationships) than do female children. And, conversely, they tend to exhibit weaker inclination towards empathy and socialising than do female children of the same age. Even from their first day of life, male babies are more interested in mechanical mobiles than are girls. And somewhere between 80%-90% of children with Asperger syndrome are male.

Though boys usually learn to walk earlier than girls, they often learn to talk much later. Albert Einstein was famously very late learning to speak – five years old by some accounts. Similar stories abound for many famous names throughout the centuries, including Thomas Edison. Recent research hints that autistic tendencies are present from shortly after birth, and there is tantalising evidence that autistic traits probably start forming before birth. Spurious claims from the late 1990s hinting that autism might be caused by environmental factors later in life such as vaccinations have since been entirely discredited by later research and the “extreme male brain” theory is now catching on.

In fact, autism seems to be triggered by a combination of developmental and genetic factors which cause the brain to form in a way characteristic of the stereotypic male brain, only more so. This means that autistic children often to have great difficulty in social interactions, being

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perceived as rude, abusive, confrontational and often spiteful, usually without even realising what they have done and without the social intuition to notice when offence has been caused.

There are, of course, many such stories for Isaac Newton. His language acquisition seems to have been normal, however. We don’t have many accounts of his childhood, but there certainly doesn’t seem to be any hint of inhibition in linguistic skills – in fact he won prizes in Greek and Latin at Cambridge. Yet children born with Asperger syndrome often have no linguistic or cognitive impairment. Newton’s behaviour, or at least those bits of it that we can piece together from first-hand accounts of his life, seems to suggest that a diagnosis of Asperger syndrome is quite a good fit. I admit, however, that it is never easy, nor particularly advisable, to attempt to retrofit diagnoses to people who have been dead for centuries.

Newton was obsessive to extremes, socially awkward, fanatical about order and neatness, unable to bear even the sight of weeds in his garden. He frequently misunderstood the intentions of his peers, and tended to seek out opportunities for isolationism wherever possible, at least in his earlier life. The truth is that we will never know where Newton lay on the autistic spectrum, but it seems highly likely that he was a fair distance along it.

What might, hundreds (or even tens) of years ago, have been explained away as the behaviour of a rude, intolerant, arrogant and aggressive man, could be seen through the light of this diagnosis as the actions of a man who, through no fault of his own, was unable to understand the nuances of human interaction, and often found himself causing great offence and alienating himself from his peers partly through his inability to read the language of subtlety and emotion in which those around him would have fluently conversed. Though it cannot be denied that Newton himself was often deliberately rude and abrasive, some of this may well have been caused by the accumulated frustration of not
being able to understand the social cues that his peers would have taken for granted.

History is full of examples like Newton – men of huge intellectual might who alienated anyone and everyone around them by displays of petulance and rudeness. Ludwig van Beethoven springs to mind as another example – a truly great genius who wrote some of the most awe-inspiring music in history whilst being functionally deaf, and was known to act erratically, with violent and offensive outbursts punctuated with rare moments of clarity and tenderness. In a famous letter of 1802, the 32 year old Beethoven writes in a letter to his brothers of the great pain of his loneliness.

“O you men who think or say that I am malevolent, stubborn or misanthropic, how greatly do you wrong me. You do not know the secret cause which makes me seem that way to you.”

Beethoven, like Newton, suffered from a lack of a relatable father figure in his early years. Though in Beethoven’s case, his father was an abusive alcoholic, determined to force his son into a life of musical showmanship for which he seemed ill-suited and unwilling. In Newton’s case, we might ask ourselves how much we could explain away his famously antagonistic nature by reference to the lack of a father in his very early years, and the distinctly unaffectionate one he later inherited through Reverend Smith – a stepfather whom a young Newton once threatened to burn alive in his house (along with his wife, Newton’s own mother). Clearly no love was lost there, but as far as we know, Rev’d Smith was not physically or mentally abusive, merely distant and aloof.

The work of Sigmund Freud that we met earlier suggested that much (if not all) of our adult personalities can be traced back directly to the (sexual) traumas that we suffer as children. The Standard Social Science Model, identified and labelled in an influential 1992 work by
anthropologists John Tooby and Leda Cosmides, dominated much of the 20th century thought, claiming that the human mind is largely a structure of the social environment in which it develops. That view, perhaps less influential than some have claimed, is nonetheless now largely rejected in favour of a hybrid model in which the existence of strong genetic tendencies has been increasingly widely acknowledged. Human action needs to be interpreted not just in the light of the experiences of childhood, but also under the very real and profound influence of the genetic factors and pre-natal environment that we now know to be responsible for a large proportion of nearly every component of human personality.

Somewhere about his fiftieth birthday, Isaac Newton suffered what we might now term a severe nervous breakdown. In his personal writings he records periods of intense melancholia, sleeplessness, fear of persecution and depression. Many theories have been put forward to explain his seemingly sudden slide into mental illness, though the lack of good evidence means that all explanations contain a necessary degree of speculation. Some suggest rather intriguingly that Newton was exposed to a great deal of mercury from his work on alchemy, and mercury is a highly toxic substance that has serious neurological implications. After his death, Newton’s hair was analysed and shown to contain substantial levels of lead, arsenic, antimony and mercury, which certainly seems to back up this hypothesis. In fact, Newton was known to have conducted taste tests (!) on a great many highly toxic substances, including mercury, which he described as “strong, sourish, ungrateful.” Needless to say, do not try this at home!

Other theories about Newton’s breakdown suggest that it might have been caused by the seemingly painful end of a long-term friendship with a young Italian mathematician named Nicolas Fatio de Dullier. Having been a close confidant (and maybe more) of Newton for several years, their friendship was suddenly broken off in June 1693 and they
rarely spoke ever again. Newton took that loss particularly badly, hinting that perhaps there might have been a romantic attachment between the two, though this necessarily remains mere speculation.

Newton’s breakdown, whatever its cause, lasted for eighteen months, in which his work and his personal relationships were all badly affected. In fact, it marked the end of the most scientifically active period of his life. Shortly after he began to recover from his breakdown, in the year 1696, Newton was appointed to Warden of the Royal Mint by the Chancellor of the Exchequer. It was a position that Newton chose to maintain until his death, and it provided him with a tidy income. In fact, this new role began to dominate his life at the expense of the scientific work at which he had previously excelled.

Though he did still find time to argue with Leibniz over the discovery of the differential calculus, and churn out a number of obscure theological works, the trajectory of Newton’s life had changed forever. Although he was to live for another thirty years, Newton achieved very little of note in science during this entire period. He published his second great work, Opticks, in 1704 – though it was largely composed of experiments he had carried out thirty years earlier. The rest of his 18th Century output was largely theological, with revised editions of Principia in 1713 and 1726 the most notable exceptions, yet it was essentially the same work that he had written when he was in his forties. It was as if the passion that so dominated his early life had dissolved away during these eighteen months of mental tribulation.

In fact, it’s almost refreshing, after so many chapters extolling the sheer superhuman brilliance of this man, despite his flaws, to watch him succumb to a very human condition. Newton’s mind, though full of scientific theories and theological postulation, was also a melting pot for all of human drama, with its attendant passions and insecurities. I am slightly inclined to wonder whether Newton wasn’t perhaps more human than the rest of us, not less. He exemplified those skills that separate human beings from our closest animal relatives – he was an
obsessive learner, right from his teens when he fanatically devoured the substantial library that he had inherited from his stepfather; He was insatiably curious – always eager to investigate, to discover, to dissect and to understand. What’s more, he expressed the whole range of human emotions, perhaps more mischievously, petulantly and even more violently than those around him, but one would have to agree that he was by no means a heartless robot or a dispassionate automaton. Those are exactly the traits that separate us from the higher primates, and they may also explain why Newton managed to elevate himself so far above his contemporaries.

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Throughout human history, the separation between good and evil has been seen as a clear-cut distinction. In the Western tradition, the existence of evil in the world has been traditionally ascribed to supernatural forces, intent on domination of the Earthly realm. Yet now we see something different. Some brains form without the capacity to understand social interaction; some form without the apparatus required to feel empathy; some lack the ability to control powerful primitive urges; some lack foresight or the ability to picture the consequences of important decisions. The 21st Century materialist scientist is forced to conclude that ‘evil’ and ‘good’, are nothing but the side effects of brains working in different ways. There is no malevolent puppet-master pulling our strings from beyond the clouds – no wide-eyed, red-skinned, trident-wielding Mephistopheles sitting on our shoulder urging us to do his nefarious bidding; there is merely the whim of our nature and nurture and the neural imprints they left behind.

Where does this leave us with moral questions? I have no intention whatsoever to launch into a theory of morality in this book – a hundred volumes each larger than this one and each written by the smartest people in the history of human thought have attempted to do that and largely failed to reach any kind of relevant conclusion after centuries of trying. Yet it seems to me at least that our theory of morality will be utterly null and void if it doesn’t contain, at its heart, the wealth of
information that the modern understanding of neuroscience has provided. The most important finding of this remarkable new learning is that the very process of understanding brings with it empathy. Once we discard the medieval notions of dualism, we realise that all human flaws stem from the same cause – the extraordinary flexibility and power of our brains which, when working in alignment with societal norms can generate the remarkable works of genius with which I have filled this book. Yet when working in opposition to those same unspoken rules, the humble human brain can unleash its power towards devastating harm.

In our twenty-first century school system children who, until fairly recently, might have been seen as wilfully obnoxious and antisocial are now integrated into lessons thanks to the knowledge that we have been able to bring to the table from the field of neuroscience. By acknowledging that certain human beings lack the wherewithal to understand the nuances of human social interaction, we have been able to empathise instead of isolate; to include instead of exclude; to understand instead of fear.

Just as, in the last few hundred years, we have revolutionised our understanding of physical disease, and we now see many common pathologies as manifestations of bacterial or viral infections rather than curses from gods or witches; Or just as we now see epilepsy as the unfortunate misfiring of neural circuitry rather than demonic possession; in exactly the same way I predict that we will eventually learn to accept all aspects of human personality – the good and the bad – as manifestations of our specific neural anatomy rather than the projection of an unseen ethereal phantom.

And, at least in principle, once we accept that others do not have the same apparatus for interacting with the world as we do, then perhaps we might reach the stage where we can approach acts of violence and selfishness as manifestations of faulty circuitry rather than following this mythological, superstitious notion of evil so common in the modern
world. And once we see personality, with all its flaws, in this way, then science may finally be able to achieve something that humanity has so far been unable to do – in the not-too-distant future, it is fully possible that science may cure evil.
Nature, Unleashed

“The changing of bodies into light, and light into bodies, is very conformable to the course of Nature, which seems delighted with transmutations.”

Newton

The human history of science has been the history of our increasing mastery over nature, with each new discovery I have outlined so far allowing us to wield a steadily increasing power. In fact, I think we can divide that process of mastery into three distinct phases, each of which has given us the ability and understanding required to improve the condition of human beings across the globe by incalculably vast amounts.

Firstly, we had to understand the world around us, so we began to explore. We measured the size of the Earth, we counted and categorised all manner of plants and animals, and we cut up and dissected everything we found to see how it worked. Almost as soon as humanity invented writing, in ancient Mesopotamia over five millennia ago, ancient scribes began to write lists of the flora and fauna of the world in which they lived.

This first era of exploration taught us about the world in which we lived, and enabled us to learn to avoid its dangers and benefit from its gifts. Once we understood the variety of animals in the world around us, we learned which ones we should fear, and which we could hunt. Once we understood botany, we began to divide plants up into those which healed, those which killed and those which spiced up a good stew. Once
we understood geology and geography, we learned where to look out for rockslides or avalanches, but also which locations would be best for our crops. This act of understanding perhaps culminated in Darwin’s great *On the Origin of Species* in 1859, though in some subjects – most notably astronomy – we continue it to this day, discovering new planets around nearby stars with every passing year.

The second stage was the age of Control: Once we understood the world in which we found ourselves, we began to work alongside nature to shape it in order to fulfil our own needs. Understanding the animals around us allowed us to domesticate the more useful ones and breed them to make them faster, stronger, more productive and meatier. Once we learned about which plants were good to eat, and how they grew, we optimised our farming with crop rotations so that we could enormously improve the yields from a diminishing area of arable land. As if that wasn’t enough, we bred our plants to increase the yields, resist pests and diseases and cope with the extremes of climate to which they were not naturally adapted.

At the same time, the mastery of electricity allowed us to harness nature’s mysterious power to drive motors and send signals across the globe. By understanding the laws of combustion and gravity, we have been able to send men to the moon and return them safely to Earth. We harnessed natural forces by building dams across rivers, protecting harbours with strong sea walls, and even today we erect windmills, water turbines and solar panels to capture energy from our environment and turn it to our own use. But within all of this, we were still following nature’s strictly defined boundaries.

Yet during the 20th Century we began to enter a third phase in our mastery of knowledge: We learned how to snatch the ultimate power out of nature’s hands. Instead of learning how best to adapt to natural forces, we started overruling nature at a fundamental level. Genetic engineering allows us to do what conventional farming and selective breeding never could; modern pharmaceutical drugs enable human
beings to live lives that nature would take from us if it were allowed to run its own course. And, perhaps most importantly, we have even started playing with that most enticing of Pandora’s Boxes: the atomic nucleus.

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Perhaps the most well-known equation in all of science comes from the fourth paper that Albert Einstein published in his miraculous year, 1905. On studying the interaction between mass and energy of moving objects, Einstein realised that all objects possessed a certain baseline quantity of energy even when motionless, and that this energy could be calculated as the product of the mass of that object and the square of the speed of light, $E=mc^2$. It is one of the few examples of a finding from theoretical physics that the majority of adults could probably recognise, yet it is also one which almost nobody could adequately explain.

The derivation of this remarkable relationship is mathematically rather complex though the implications of this simple formula are not very difficult to grasp. Einstein’s equation tells us not just that mass and energy are related in some way, but that they are actually two sides of the same coin – they are, essentially, the same thing in different forms. Like the water that flows from your tap, and the ice you see on frozen lakes – the same substance in two different forms with very different properties. Except in the case of matter and energy this difference seems far more profound, which means that the claim of identity is far more difficult to accept.

In exactly the same way that you can measure length in miles or kilometres, with a conversion factor of 1.6 between the two\(^91\), you can also measure energy in Joules or Kilogrammes, with a conversion factor of $c^2$, or roughly 90 million billion between the two. The Joule, named after the English physicist James Prescott Joule (1818 – 1889), is the standard unit of energy. One joule is roughly the kinetic energy of a

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\(^91\) One mile is fractionally more than 1.6 kilometres, so if you have a distance measured in miles you can easily convert it to kilometres by multiplying by 1.6.
table tennis ball moving at high speed after being struck, or the energy it takes to lift a banana from the floor and feed it to an adult male gorilla, or the energy required to stack seven hamsters on top of each other. It’s a fairly convenient, human-comprehensible quantity.

The equivalence of mass and energy is, I admit, not the easiest concept to accept. Energy is generally associated with the warmth of the Sun or a roaring fire, the light of an incandescent bulb or the whirring of an electric motor. Energy is active, kinetic, dynamic. Mass is heavy, stationary, inert. They seem to be opposites, at least on a human scale.

Yet energy isn’t just a dynamic force – all objects in the Universe also possess another kind of energy – potential energy. Potential energy is unlike kinetic energy in that it can’t be seen, felt or heard – it’s merely a hidden quantity, a promise of things to come. You gain potential energy as you climb a set of stairs, but to any observer watching you ascend, nothing about you has visibly changed.

Let’s imagine a thought experiment, and for purely aesthetic purposes, let’s run it at the Leaning Tower of Pisa in Italy. Imagine you stand at the bottom of the tower with a heavy cannonball in your hands. You start to climb up the stairs, carrying the cannonball with you, and as you do so, with every new step, the cannonball gains gravitational potential energy. You can think of this in exactly the same way that you would a rechargeable electric battery. As you charge the battery, it gains electrical potential energy. The main difference is that the ball has been ‘charged’ not by electric current but by your muscles expending energy to climb the 296 steps to the top of the tower.

Each step you climb upwards, fighting against the Earth’s gravitational pull, is in essence charging the cannonball (and your own body, of course) with gravitational potential energy. As you reach the top, exhausted, the ball will have gained around three thousand joules of potential energy (or three kilojoules, kJ). Being an anarchist as well as an eager experimentalist, you decide to drop the ball from the tower and
see what it does to the pavement below. The instant you let go, the gravitational potential energy stored up in that cannonball begins to convert into kinetic energy (movement) as it plummets towards the ground below. As the cannonball accelerates, the gravitational potential energy drops and the kinetic energy increases by the same amount. Then, a fraction of a second before the cannonball strikes the floor, the potential energy is back where it started, yet all the extra energy gained from your strenuous climb is now manifested entirely in the form of kinetic energy (minus a bit wasted fighting against wind resistance). As the cannonball strikes the stone pavement, with an almighty crash the kinetic energy is finally dissipated as a mixture of heat and sound. The tourists scatter, the police are duly summoned, but the work of science is done.

Though some have argued that Newton had thought about the conservation of energy, it can reasonably be assumed that he didn’t understand it in anything like its modern form. For one thing, the exact nature of kinetic energy wasn’t really discovered until the early 1800s. And then in 1843 it was the same Monsieur Joule, who gave his name to the unit of energy, having been (debatably) the first to understand the cycle of gravitational energy, kinetic energy and heat that I have just described. As the theory developed, scientists began to realise that all the complexity of the visible Universe could be thought of as the endless dance of energy, flitting from form to form sometimes rapidly, sometimes slowly, sometimes quietly, sometimes spectacularly.

Then in 1905, Einstein showed just how true this picture actually was, with his intriguingly-titled 1905 paper “Does the Inertia of a Body Depend Upon Its Energy Content?” The answer, it turns out, is “Yes”. There is a law of newspaper headlines called Betteridge’s Law, which states that any headline posed as a question can always safely be answered with the answer “No”. It turns out that the reverse is usually

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92 Named after British journalist Ian Betteridge. Illustrated perhaps most prominently by sensationalist tabloids.
true with scientific papers. In general, scientists don’t pose tantalising questions unless they’re pretty sure that the answer is interesting.

So the entire Universe is built from energy in all its various guises. In a sense, this was much like Newton’s observation that the laws of dynamics were just based on an object’s mass – it simplified the picture from the more complex Aristotelian view that everything was composed of four elements in complex mixtures. And now, Einstein’s discovery simplified the Universe even more because he realised that mass and energy – previously seen as completely unrelated properties – were, in fact, the same thing. And that discovery would prove to be extremely important as the twentieth Century began to unfold.

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Looking at a lump of Uranium you would be forgiven for thinking that it was a rather uninteresting material – dullish grey, surprisingly heavy yet otherwise unremarkable to the unaided observer. Until, that is, you investigate it with a device able to pick up the emission of high energy radiation, when all of a sudden the dials go crazy, lights flash wildly and alarm bells start sounding. Although it appears inert to the naked eye, a sample of Uranium is constantly emitting a barrage of highly dangerous yet invisible particles which, until a few years before the turn of the twentieth century, had gone entirely undetected by everyone.

It has been known since Roman times that glass made with small amounts of pitchblende (an ore rich in Uranium) developed a pleasing yellow colour, and was later discovered to glow an eerie yellow-green under ultraviolet light. In the early 1900s, glass was often made with up to 25% Uranium by weight for precisely these novelty properties. At the same time, scientists were discovering that Uranium was just one of a wide range of elements that gave off invisible rays that could be measured on photographic film, and it became a matter of great interest to understand the nature of these substances and whether or not this intriguing new discovery could in some way benefit humanity.
Of all names associated with this new field of study, perhaps the most well-known is Marie Curie (1867 – 1934) who, together with her husband Pierre, carried out much of the pioneering work that effectively founded an entire academic discipline. Marie Curie was the first woman ever to win a Nobel Prize, and she remains to this day both the only woman ever to win two Nobel Prizes, and the only person ever to have gained Nobel Prizes in two different sciences (Physics and Chemistry).

Curie was born Maria Salomea Skłodowska in Warsaw, Poland. As a student, she studied first in Poland, then in the Sorbonne in Paris, where she dedicated her life to physics and eventually carried out most of her ground-breaking research. It was also in Paris that she met her eventual husband, a lecturer at the Ecole supérieure. It had always been Marie’s plan to return to Warsaw and work there, but she was rejected from that post because she wasn’t a man (apparently the faculty considered this important) so she indignantly returned to Paris and dedicated her considerable skills to that mildly less sexist city instead. Marie and Pierre were married within a year, and began a new life, not only at home, but also in the laboratory together. Their chosen topic of research – Uranium.

Uranium was where it all began. It was with this otherwise unremarkable metal that the Curies’ colleague Henri Becquerel (1852 - 1908) first discovered, in 1896, its ability to darken photographic plates by the emission of invisible rays. The standard unit of radioactivity is named in his honour. Marie and Pierre continued Becquerel’s work, learning how to isolate Uranium from its ores, and comparing the various properties of the substances that they had collected. The Curies also actually coined the term “radioactivity” for this hitherto unknown behaviour.

As part of their research into the properties of Uranium, the Curies also discovered the radioactive nature of the element Thorium, although
fractionally beaten to the goal of publishing their work by a German researcher, Gerhard Schmidt. Yet they were definitely the first to record the discovery of two entirely new elements which they called Polonium (after Marie’s country of birth) and Radium (after the Latin word for “ray”).

In 1903, Marie and Pierre were jointly awarded the Nobel Prize for Physics, along with Henri Bequerel, for their work on the study of radioactivity. Marie was the first woman ever to earn this great honour and, in an age before universal suffrage, the achievement was all the more astounding. It seemed like everything was going perfectly for the remarkable husband and wife team.

Sadly, their future did not hold a great deal of happiness. On 19th April 1906, Pierre Curie was crossing the Rue Dauphine in Paris in heavy rain when he was struck by a horse and carriage. He was crushed under the heavy wheels and killed instantly. Devastated, Marie vowed to continue the work that they had started together and she was awarded her late husband’s post at the University, the first woman ever to hold a senior academic position at that institution. She rededicated herself to the cause that she and Pierre had so fervently pursued together, and continued to make many new discoveries.

Marie won her second Nobel Prize in 1911, this time in Chemistry, for the discovery of Radium and Polonium. Then in 1914 war broke out, and she dedicated her talents to providing battlefield medicine through a fleet of mobile, truck-based x-ray machines. She continued to receive nearly zero recognition for her work from the French government, despite her two Nobel prizes and widespread international fame – such was the plight of even the most brilliant women in a society that still considered them second-class citizens.

Yet despite the rejection and lack of recognition, Curie continued her research in radioactivity well into the inter-war years and continued to publish world-leading results. However, the Uranium was now taking
toll and her health had begun to deteriorate. With each year she grew progressively weaker as the highly toxic substances that she was studying tore apart her body’s vulnerable cells. On 4th July 1934 she finally died of aplastic anaemia – a disease of the bone marrow which is often caused by acute radiation poisoning.

In perhaps the most remarkable example of children following in their parents’ footsteps, Marie and Pierre’s daughter, Irène, also went on to study chemistry, also married another chemist (Jean Frédéric Joliot), also worked on the field of radioactivity, and also went on to share the Nobel Prize for her work with her husband. Irène also went on to die from radiation-induced cancer (leukemia in her case) and also had two children who decided to become highly decorated researchers in their own right – Hélène Langevin-Joliot (a nuclear physicist, whose son is a noted astrophysicist) and Pierre Joliot (a biochemist). Marie Curie’s other daughter, Eve, may not have achieved a Nobel Prize herself, though she did marry American diplomat Henry Richardson Labouisse, who received the Nobel Prize for Peace as director of UNICEF in 1954. Five Nobel laureates in two generations would be an impressive achievement for a nation, but for one family it is nothing short of legendary, and has not come close to being equalled since. In 1944, the radioactive element Curium was named in honour of this remarkable dynasty, and deservedly so.

The Curie family, though clearly rewarded to an unparalleled degree by the international scientific community, had also been badly scarred by tragedy. Pierre’s cruel, early death robbed the young family of a father and husband, and radiation sickness killed off Marie herself and her eldest daughter. It is likely that Pierre would have suffered a similarly gruesome fate to that of his wife if he had survived to continue his work. Yet the dangers of radioactivity were not known at the time the Curies were carrying out their research – to them it was a scientific curiosity, not a threat. Marie often carried test tubes full of deadly radioactive substances in her pocket and stored them in her desk drawer when she wasn’t using them. Her research papers from the late 19th
Century are still, even today, considered too radioactive to be handled without special protective apparatus, and are stored in a lead-lined container for safety.

Before the danger of radioactivity became apparent, a number of radioactive products started to appear on the market, for sale to the general public. And this time it wasn’t just novelty glow-in-the-dark glassware, but also uranium blankets that supposedly relieved arthritis, and perhaps most famously of all, Radithor – the ‘healthy’ water laced with thorium (mildly radioactive and toxic) and radium (highly radioactive and extremely toxic) that first hit the market in 1918. Radithor was believed to be a wonder tonic – good for all manner of ailments; yet unknown to its manufacturers their healthy tonic contained a deadly threat. The alert was raised after the death of one famous athlete and socialite, Eben McBurney Byers, who died in 1932 of multiple cancers as the effects of his three-bottle-a-day Radithor diet caught up on him. He estimated that he had consumed roughly 1400 bottles in his lifetime – a terrifyingly high dose of deadly radioactive substances poured directly into his alimentary canal. The Wall Street Journal ran a beautifully understated post-mortem article on his case, entitled “The Radium Water Worked Fine Until His Jaw Came Off”.

Fig. 11: Radithor – a few bottles of this and you won’t suffer from disease ever again! Source: www.orau.org
After the death of Eben Byers, and a number of other deaths caused by ridiculously dangerous substances on sale as medicines, the US Congress vowed to strengthen the powers of the Food and Drug Administration, who promptly put an end to this whole toxic industry.

Even without anecdotes like that of the Radithor fiasco, the history of research into radioactivity is littered with tragic and utterly preventable deaths. Reading about the crazily hazardous things scientists used to do before they fully realised the threat of radioactivity fills me with an imminent and uncontrollable sense of unavoidable doom. From our privileged position in the 21st Century we can see the danger coming a mile off, but they couldn’t, and they usually paid the ultimate price for their ignorance.

It is almost impossible to avoid the comparison with Newton here, who went to reckless lengths to investigate the laws of nature. On one occasion he carried out an experiment into the effects of applying pressure to the human eye. *His* human eye. He performed this experiment by inserting a needle “betwixt my eye & bone as neare to [the] backside of my eye as I could”. He then proceeded to press against the eyeball, and made notes on the strange visual apparitions that it produced. His eyes escaping from this abuse largely intact, he then proceeded to stare directly at the sun for extended periods of time, very nearly blinding himself in the process. It took over a week, primarily spent in a darkened room, for his eyesight to recover from the ordeal.

Scientists often go to great lengths in pursuit of the truth, and Newton was one of the lucky ones, avoiding major injury. I can only imagine the furore his experiments would cause today in front of a health and safety review board – and rightly so. The Curie family sacrificed rather more, though their legacy lives on into immortality and the discoveries that they provided have enriched the human race beyond measure.

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The radioactive properties of Uranium have spun many a tragic tale, and yellow glow-in-the-dark glass has a certain novelty value, yet the most important property of Uranium was finally discovered shortly before Marie Curie’s death, by the legendary Italian physicist Enrico Fermi (1901 - 1954). Fermi lived most of his early life in Rome, which was here he set up his physical laboratory, yet he was forced to flee Italy in 1938 to avoid the onslaught of Mussolini’s encroaching fascism. For Fermi, leaving Europe was of particular importance as his wife had Jewish ancestry, and he rightly feared that she might be rounded up and sent off to a concentration camp were they to have stayed.

Yet as the Fermi family fled the horrors of Nazi persecution, they stopped off in Stockholm en route to the US to pick up the Nobel Prize in Physics for a study Enrico had published just four years earlier, on the subject of radioactivity and how to induce it in certain substances by bombarding them with high energy neutrons. Little did Fermi know, but just a decade later this very research would lead to the construction of the most potent weapon ever known, developed by an international team of scientists working for the sworn enemy of his former homeland.

Fermi’s study of Uranium had taken a different route to that of Marie Curie. Uranium is a very large atom – roughly seventeen times more massive than an atom of Carbon, containing 92 protons and between 141 and 147 neutrons, depending on which variety you’re dealing with. The most commonly found variety, or isotope, is Uranium-238, containing 92 protons and 146 neutrons. This would have formed the basis for the bulk of Marie Curie’s work. Yet for our purposes, the most interesting isotope is Uranium-235, which is far rarer, making up less than one percent of the Uranium found naturally on Earth. However, this slightly lighter variety of Uranium has one particularly important property, unique amongst all naturally occurring elements – if you give

\[93 \text{ Isotopes are versions of the same element (i.e. they have the same number of protons in the nucleus), but with a different number of neutrons.}\]
Uranium-235 a big enough jolt, it splits in two and emits a huge quantity of energy.

This process, known as Nuclear Fission, is a direct consequence of Einstein’s mass-energy equivalence and, though related to radioactive decay in some sense, it is actually caused by a completely different process. U-235 does radioactively decay too, with a half-life\textsuperscript{94} of over 700 million years, to Thorium-231, yet this decay is so slow that no substantial amount of energy could ever be harvested from it.

The fission reaction is remarkably simple: when a U-235 atom is struck by a sufficiently fast moving neutron, it splits into two smaller fragments, plus three more neutrons. If you add up the mass of the neutron and the Uranium beforehand, and compare it with the mass of the three neutrons and remaining fragments afterwards, then you notice that there is some mass “left over”. Admittedly not a lot of mass – on average something like one tenth of one percent of the mass of the original atom. But if you recall, mass and energy are directly equivalent and the scale factor is the square of the speed of light – or ninety thousand million million - so this tiny amount of mass equates to an emission of a measurable amount of energy. Of course human-scale objects don’t behave like this. If you cut an apple in half, you would expect the two halves to sum together to exactly the same mass as the original apple. But physics doesn’t work like that on the atomic level. When you stray far from the scale in which we humans usually carry out our daily lives, then physics becomes very weird indeed.

The fission of a single atom of Uranium produces a miniscule quantity of energy – completely undetectable on human scales. Yet there are something like two and a half million million million million atoms of Uranium in just one kilogram of the stuff, and the effect adds up rather

\textsuperscript{94} Radioactive decay is a random process, so decay rates are measured in terms of the “half life”, which is the period of time over which half of any original sample would statistically be expected to have decayed. A long half-life means the decay is slow, whereas a short half-life means that it decays rapidly.
rapidly. In a nuclear power plant, large rods of Uranium are bombarded by neutrons with exactly the right energy to kick-start a fission reaction, and with so many atoms available a colossal amount of energy can be produced.

But you will probably have noticed something I skipped over earlier – namely that the fission of Uranium produces *three more neutrons*. And those three neutrons don’t just sit around doing nothing – they shoot off in random directions, and a few of them will strike other Uranium atoms and trigger them to split too. These events will release three more neutrons, and so on. This is what’s called a *chain reaction*, and it’s the process that makes atomic weapons so powerful – it takes just a single neutron to trigger the catastrophic fission of countless trillions of Uranium atoms in a tiny fraction of a second.

The degree to which this process gets out of control and generates an unstoppable runaway explosion depends on how many of these energetic neutrons actually strike other U-235 atoms. If it’s more than a third then the reaction will continue, because the number of neutrons flying around will increase with each collision. The greater the fraction of the neutrons that strike other U-235 atoms, the more ferocious the chain reaction will be. If fewer than a third of the released neutrons strike another U-235 nucleus, then the reaction will gradually die out because, at each step, there will be fewer and fewer free neutrons on average.

Of course, the tremendous release of energy from nuclear fission can be captured for beneficial purposes. However, to stop the reaction from going out of control – which seems like the sort of thing that you might want to do – you need take a few precautions. Firstly, you don’t enrich the Uranium too much. Uranium, if you recall, in its natural state is 99% U-238, which does not react in this way, and something like 0.7% U-235. In naturally-occurring Uranium, if you manage to get a U-235 atom to split, then the three neutrons released will almost certainly not strike another U-235 atom simply because almost all of their neighbours
are U-238. If they hit U-238 then they get absorbed and the reaction stops. So the Uranium needs to be enriched to increase the fraction of U-235 in the material and thereby increase the chance that a stray neutron will hit a U-235 atom and continue the chain reaction.

To do this, we rely on the very slight difference in mass between U-235 and U-238 – because the latter has three more neutrons in its nucleus. So if we spin a mixture of these two in a centrifuge, then the U-238 will move to one end and the U-235 to the other. The difference isn’t enormous, but it’s enough to refine the Uranium and gradually increase the fraction of the valuable U-235 isotope. And once you get to something in the range 3% to 5% of U-235 – and no more – then you’re good to go.

The second way we calm down the runaway fission of U-235 in nuclear reactors is by surrounding the Uranium with other elements that readily absorb the free neutrons as they are released. Long, thin cylinders of Uranium are then lowered into a pressurised container full of water, which heats up as the Uranium releases its nuclear energy. This hot water circulates round and dumps its heat into water baths via heat exchangers – basically giant underwater radiators. The waters never mix – the water in the reactor is kept entirely separate from the water in the generator. The cooled reactor water completes its cycle back round to the Uranium rods again to be reheated. On the other side of the heat exchanger, the generator water heats up until it eventually boils off, and the resultant steam is used to run turbines connected to enormous generators.

In a nuclear reactor, one kilogram of Uranium is theoretically enough to produce the same energy as three thousand tonnes of coal – or approximately thirty railway carriages full. And it does so with the emission of no greenhouse gases, no soot and, because the entire reactor is a sealed unit, it actually releases far less radioactive material into the
atmosphere than coal-fired plants. A 2013 report from Stuttgart University estimated that pollutants from coal-fired power stations in Europe alone cause 22,000 premature deaths and a loss of approximately 240,000 years of life each year across the continent.

One question that might have occurred to you is – what if naturally occurring Uranium ever got together in such large amounts that it underwent natural fission all by itself? Well, surprisingly, this has indeed happened at a site called Oklo in the West African nation of Gabon. The so-called natural fission reactor – the only known location at which this has ever occurred – generated enough energy at its peak to power a small village. This isn’t still happening today, unfortunately; it seems that the reactor was only in operation around 1.7 billion years ago, long before multi-cellular life first appeared on Earth. In fact, even when the reactions began they only lasted for a few hundred thousand years. Yet during that time, a sustained fission reaction was gently warming the land of ancient Gabon.

We only know that this remarkable natural coincidence actually happened because a French Physicist called Francis Perrin (1901 - 1992) discovered in 1972 that there was slightly less U-235 at the Oklo site than would be expected in naturally-occurring Uranium ore. Scientists also found higher traces of the elements into which U-235 transforms during fission. By comparing the amounts of each, and through a little bit of maths involving the relevant half-lives, it was possible to work out when this all happened and for how long. The Oklo reactor is a great example of how scientists can make extraordinary deductions about a time far in the distant past purely by examining the properties of the world today.

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95 Coal contains between 1-10 parts per million Uranium and the US energy industry burns roughly 1 billion metric tons of coal per year. Taking the optimistic values, that’s still one thousand tons of Uranium per year dumped into the environment from coal burning in the US. Fortunately, it turns out that the impact of that is negligible unless you live right underneath such a power station.

96 Published June 2013 by Greenpeace International
The Oklo reactor was a slow, simmering deposit of naturally enriched Uranium. But what happens if we don’t attempt to contain the power of nuclear fission and allow a chain reaction to occur uncontrolled? Well, this is exactly what happened on August 6th 1945 just above the Japanese city of Hiroshima – tragically thrust into the history books as ground zero for the first ever aggressive detonation of an atomic weapon. The bomb, codenamed “Little Boy”, contained 64kg of Uranium, enriched to the 80% level on average. Roughly 1% of this Uranium actually underwent fission in the blast before the force of the explosion scattered the remainder far and wide.

The bomb was dropped from a Boeing B-29 Superfortress Bomber, flying ten kilometres above the city. It fell for 43 seconds before detonating 600 metres in the air, releasing an explosion equivalent to 15,000 tons of TNT. Within seconds, an all-consuming fireball had annihilated the centre of the city, and instantly incinerated 66,000 men, women and children. Anyone within two kilometres of ground zero stood no chance of survival. A fireball of 6,000 degrees Celsius immolated the region around the initial explosion, and then sent out a supersonic blast wave that flattened nearly all structures nearby. Moments afterwards, a raging firestorm consumed anything unlucky enough to have survived the initial blast. Modern estimates place the eventual death toll at well over 100,000 human beings, executed in a few seconds by six hundred grams of dull silver metal.

In fact, as I mentioned earlier, the actual quantity of mass converted into energy when a Uranium splits in this way is a small fraction of the mass of the Uranium itself – roughly a tenth of one percent. So if you add up all the energy released in the Hiroshima blast and calculate how much mass it actually corresponds to, it works out at roughly six hundred milligrams, or approximately the mass of a small raisin.

The Little Boy bomb was the result of several years of concentrated work by many of the world’s greatest physicists in a frantic and
immensely costly exercise that cost billions of dollars and, at its peak, employed roughly 130,000 people – many of whom probably never knew what it was that they were working on. In fact, the project was so secretive that the Hiroshima detonation would genuinely have come as a surprise to the vast majority of those men and women who had been unknowingly working towards it for years. One can only imagine what they must have thought when the end of their labour had finally been revealed, and the true horror of mankind’s new weapon of annihilation was unleashed on an unsuspecting world. As the iconic mushroom cloud rose ominously into the skies over Japan, they might perhaps have echoed the words of physicist J. Robert Oppenheimer (1904 – 1967) who, having jointly led the US atomic weapons research effort and subsequently contemplated the devastation which he had helped to unleash, quoted the Hindu scriptures of which he was so fond and pronounced “I am become death, the destroyer of worlds”.

Although fission was a technology primarily developed for warfare, its discovery does at least answer one puzzle that had consumed much of Newton’s life, and which we touched on a few chapters ago. Through Einstein’s understanding of the Mass-Energy equivalence, and the work done in the early twentieth century on the physics of the atom, we finally learned how a scientist with the right apparatus could turn base metals like Lead into Gold. Admittedly, in this case the “right apparatus” was “a particle accelerator”, so the physicists of the turn of the twentieth century were still a long way off (and Newton much more so), but at least the alchemists weren’t totally wrong.

Lead atoms contain 82 protons, otherwise known as its “Atomic number”, and usually between 124 and 126 neutrons, depending on which isotope you’re using. Gold atoms have 79 protons and 118 neutrons. So to turn Lead to Gold, we need to “chip off” those extra three protons and six to eight neutrons. Well, it turns out that it requires a fair chunk of energy (plus a bit of luck) to turn Lead into Gold. But let’s say we actually want to try this hare-brained scheme. Then what? Well, for one thing, you can’t just supply energy to an atom and expect
it to immediately reassemble into whatever you actually want – the number of different particles that could be formed when you bombard a sample of lead is huge, and the chance of everything working perfectly and us ending up with one gold atom at the end is negligible. But let’s overlook that – let’s say that we want to use a particle accelerator to achieve what centuries of alchemists dreamed of. How would that work?

Well a particle accelerator pretty much does what it says on the tin – it’s an enormous tunnel, usually in a closed circle, around which particles race at ever increasing speeds, accelerated by gigantic magnets, until they slam into each other and all that kinetic (movement) energy is translated to other forms – a combination of heat, light and new particles (i.e. mass – remember that’s just another form of energy). What we really need to do is to get two lead atoms, smash them into each other really fast, and look for gold.

Amazingly, it seems that this feat may actually have been achieved. Lead has been turned into Gold by physicists on possibly two occasions, once in 1972 and later in 1980. The earlier claim proves remarkably difficult to verify – that Soviet physicists discovered the lead lining of an experimental reactor had been partly turned to gold during the course of the research they had been carrying out. There was only a tiny amount, not exactly enough to start a jewellery firm, but the discovery was of great significance. Even though they probably hadn’t much thought about it at the time, and it certainly wasn’t the aim of their experiment, those Soviet physicists had succeeded in achieving the goal towards which alchemists had striven for centuries. The life’s work of Isaac Newton didn’t even scratch the surface of the alchemical dream, but now, in the late 20th Century, Science had achieved what alchemy could not.

Though the Soviet story is unverified, I like to think that it probably happened. But even if we discard that claim, the second story is more plausible, and concerns Nobel-prize winning physicist Glenn Seaborg
(1912 – 1999), who definitely transmuted Bismuth (Atomic number 83, one higher than Lead) into Gold (atomic number 79). And the expectation, though unproven, is that this process must have taken place via Lead as an intermediate stage.

So next time someone tells you it’s impossible to turn Lead into Gold, you will know better. And you will also no longer find it all that surprising that Newton, despite his towering intellect and pathological obsession with the task, utterly failed to do so.

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So that’s fission – splitting large nuclei into smaller chunks and releasing energy in the process. But, as it happens, you can achieve something similar from the opposite direction. Nuclear fusion is the process of combining small nuclei together to make larger ones and releasing energy in the process. Which sounds strange at first glance – how is it possible that splitting atoms creates energy, and so does joining them together? Well the answer is that I have slightly glossed over one important fact, which is that fission only works when you’re dealing with atoms heavier than Iron, and fusion only works for elements lighter than Iron. The reason for this is that Iron is the most stable element, in a nuclear sense, because the protons and neutrons in an Iron nucleus are bound together more strongly than in any other element. This means that, in order to split Iron into smaller elements, or to combine two iron nuclei into a larger element, you have to put in a lot of energy into the reaction – far more than you get back out. Fission and fusion reverse that process, and hence are able to liberate some of that excess energy.

Nuclear fusion is one of the most vital processes in the Universe, without which almost nothing we see could exist. Fusion is the process by which the stars generate their colossal energy output. In the core of our Sun, Hydrogen is being converted to Helium through nuclear fusion on a truly awe-inspiring scale – six hundred million metric tonnes of
Hydrogen are swallowed up every second within our star’s voracious core, and that has been going on for over four and a half billion years.

Of all the future technologies that offer extraordinary potential for the human race, fusion power must be among the most exciting. The challenge is in learning how to harness it for our own purposes. If we could achieve this extraordinary feat, we would solve all the energy needs of the entire human race forever. Rarely does any one single field of research offer such an extraordinary benefit with essentially zero drawbacks.

Conventional fusion power research has concentrated on fusing Deuterium (a heavy isotope of Hydrogen) and Lithium (the third lightest element) into Helium\(^97\). Just in the seawater that covers two-thirds of the surface of the Earth, there is enough Lithium to power all of human civilisation for tens of millions of years. If we instead opted for a Deuterium-Deuterium process (more difficult, but still plausible) then we have more than enough fuel in the oceans to last us until long after the death of our Sun and the destruction of the solar system.

Remember that fusion power is almost entirely clean, with no radioactive by-products, no CO\(_2\) production, and no dangerous waste to dispose of. It is by any standard the greatest hope we have for long-term sustainable, carbon-free energy generation. Yet even after well over half a century of progress, controlled, sustainable nuclear fusion still remains very much a technology of the future.

It’s not fusion reactions that are difficult to achieve – we can certainly do that without too many problems. The main issue is that we need to keep them under control. And once we’ve done that, the second hurdle – even more difficult than the first – is that we need to do so in a way that produces more energy out than we put in, otherwise what’s the point?

\(^{97}\) It turns out that this is the sole exception to the rule that smaller elements exclusively fuse into larger ones.

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Generating runaway uncontrolled fusion reactions has been achievable since the 1950s, not long after the first fission bomb was dropped. The basic design involves a conventional fission bomb which is used as a trigger for a fusion device inside. The fusion device also generates a vast flux of high energy neutrons, which interact with the remaining fissile material, igniting more of that and amplifying the device’s destructive power. The first such device was tested in 1951, and the second in 1952. Within a decade, devices far more powerful than the bomb dropped on Hiroshima could be fitted on a missile capable of reaching anywhere on Earth. Stalin, with barely a year left to live, knew that the Soviet Union had to catch up or else surrender global power to the United States. As one of his last acts, he put in place a programme that led, five months after his death, to the Soviet researchers detonating their own fusion bomb in a remote part of Kazakhstan. The nuclear arms race had begun with a vengeance.

At the peak of the cold war, the Americans and Soviets possessed 70,000 nuclear warheads between them. If each one killed 100,000 people, like the bombs dropped on Japan, then those arsenals together could have killed 7 billion people, which is roughly the present day population of Earth. Yet most of those warheads were much more powerful than the ones dropped on Hiroshima and Nagasaki, so the death toll would have climbed even faster. On 30th October 1961, the Soviets tested the so-called Tsar-Bomba, the most powerful weapon ever detonated by our species, with a yield of 50 Megatons of TNT, or well over a thousand times more destructive force than the Hiroshima and Nagasaki bombs combined. In fact, perhaps more chillingly, this one single weapon possessed a power equal to fifteen times the total energy released by all explosives used throughout the entirety of the Second World War (including the two US atomic devices). There is no exaggeration whatsoever in saying that since the middle of the Twentieth Century human beings, for the first time in history, have possessed the means to send our entire species to extinction.
Since the advent of atomic warfare, and throughout the second half of the Twentieth Century, it seemed like we were running as fast as we could, scrambling to develop the technology required to build increasingly devastating weapons of mass destruction. Yet, fortunately, we stopped just short of the precipice. Now, several decades on, we have backed off from the edge and towards safer ground. The global number of deployable warheads has been greatly reduced since the peak of the cold war, dropping from a maximum of 70,000 to something like 4,000 active warheads today, with maybe four times that number held in secure storage. It’s a significant reduction, though it should be stressed that there is still ample destructive power in those few thousand weapons to wipe out our entire species in a matter of hours.

With that thought still fresh in our minds, I suppose now might be a fitting time to discuss that age-old question – is Science a force for good in the world? Could we argue that humankind was better off before the invention of the atomic bomb? It seems like a simple question with an equally obvious answer, but I think it merits investigation. There are lots of arguments one could make – for example, the firebombing of Tokyo with conventional weapons caused many more deaths than the atomic bomb at Hiroshima, and it has been argued that the dropping of the two atomic bombs on Japan brought the Second World War to a more rapid close, potentially saving hundreds of thousands of lives that might have been lost if the war had continued.

Moreover, sixty years of nuclear power plants have saved a great deal of CO₂ being released into the atmosphere, and therefore given us a small buffer of time to sort out Global Warming before it leads to unstoppable and devastating climate change. Research into nuclear fission has helped us to understand a great deal more about the Universe around us, including the engine at the core of our planet that provides half of the Earth’s heat. And there’s an argument that the development of sufficiently powerful weaponry has removed the incentive for warfare, and hence led to seventy years without any further conflicts of a scale to rival the Second World War. Without the threat of mutually
assured destruction, who’s to know whether the Soviet Union might have gone to war with the USA in the second half of the twentieth century? What might have been the outcome of such a titanic battle?

On the other side of the balance, nuclear weapons provide a very real and terrifying threat to the survival of our species, and nuclear accidents like that at Chernobyl, Ukraine in 1986, have the potential to cause widespread suffering and devastation across an entire continent.

But it isn’t about the balance of deaths vs. lives saved – scientific discoveries have been providing us with increasingly potent ways to kill each other for thousands of years, from the first weapon smiths who learned how to smelt metal ores into usable blades, through catapults, gunpowder, crossbows, rifles, machine guns, ballistic missiles and stealth bombers. The argument attempting to claim that “scientific advances that lead to weaponry are all of negative value to our species” simply doesn’t work, unless you think that society went downhill the minute someone learned how to smelt bronze to make slightly better axes.

Even the most innocent discoveries could be used for ill. 3D printers promise to revolutionise the consumer economy, and provide a way to produce complicated parts for all sorts of vital devices extremely cheaply, quickly, easily and stronger than ever before – yet of course, it was only a few months after they became available before someone worked out how to build a usable handgun with one. We have created mobile phones that allow us to be in contact with our friends, colleagues and loved ones wherever we want – yet organised crime gangs also use them to control their murderous empires; We built rockets that can launch our most exciting astronomical observatories into space, and landed twelve men safely on the moon, but they can also be used in a time of war to strike military targets across the globe; We invented the Internet, the greatest repository of information ever known, in which we can learn from the finest minds of our time and share in the wealth of human discovery – yet a few criminal gangs use it to
coordinate and profit from espionage, extortion or child abuse. Technology can always be used for evil, but it can also be used for good, and the evil is usually disproportionately over-reported whereas the good usually goes without a mention in the popular press. It’s very difficult to report on the thousands of babies who didn’t die today because of medical science.

Scientific discoveries cannot be “undone”. Now that we have the pervasive, distributed global information sharing that the Internet provides, it is not overstating the mark to say that our society has lost the ability to forget. This is an enormous strength of the modern world, but it is also a source of great potential danger. The power that science has brought us, coupled with the inability to banish our most troubling discoveries, poses a complicated moral dilemma for our entire society. As we push aside the darkness, we take the risk that we discover demons hiding in the shadows that we can never banish.

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Thomas Babington Macaulay, 1st Baron Macaulay (1800 – 1859) joins Isaac Newton in the antechapel of Trinity College Cambridge. As one of the foremost historians of his time, he wrote much about the condition of man throughout the ages. Although he concentrated on late medieval Britain, that one period alone brought more than its fair share of warfare, coinciding with ferocious clashes between the expansionist Ottoman Empire and the established European powers. He is an ideal commentator on the responsibility that is inevitably thrust on those who would gain power through knowledge or military force.

Macaulay knew from his studies of history that one thing distinguished the greatest figures in history from all others. “The highest proof of virtue,” he wrote, “is to possess boundless power without abusing it.”

This is the noble goal towards which science always aims, and it is a test that the scientific community has had to face to an ever increasing

98 From Macaulay’s Review of Aiken’s Life of Addison (1843)

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degree over the last century. As scientific enquiry has encroached more visibly on our daily lives, the responsibility of research has grown tremendously. The discoveries we make today have the potential to destroy civilisations or to revolutionise human wellbeing, and the separation between those two outcomes is often perilously narrow.

The noble aim to possess power without abusing it is perhaps a standard against which Isaac Newton fell short. Newton gained a great deal of power and influence from his scientific fame, and he abused it continually to punish those who disagreed with his ideas. I find it difficult to believe that money by itself was ever much of an incentive, but the ability to wield power over those who had maligned him was clearly an attractive goal for a man who had been bullied as a child and was never the kind to forgive and forget.

After a life of extraordinary achievements, Isaac Newton was at long last rewarded by the crown in 1705, when he finally became Sir Isaac Newton. Surprisingly, Queen Anne knighted him not for his extraordinary contributions to science, but for “Services to Politics”. Newton had resigned his University position in 1701, and though he still dabbled in the Natural Sciences, his mind was largely elsewhere.

It seems puzzling that such a towering figure of the scientific world should be recognised with a knighthood for something for which he is almost never remembered - rather like if Stephen Hawking were renowned merely for his cameos on *The Simpsons*. Yet Newton’s life had taken a very substantial turn away from the academic world in which he had displayed his most profound talents.

I began this chapter with a broad claim that the history of science could be broken down into three phases, of Understanding, Control and Mastery. The remarkable success of nuclear physics demonstrates our ability to harness nature for our own ends, not merely working with it, as those 19th Century water-powered cotton mills may have done, but breaking down what nature had given us into its constituents, taking
what we wanted and extracting from it an unimaginable power. And in this, we have achieved what Newton singularly failed to achieve – we have gained control over the elements of nature in a way that his alchemy was never able to provide. And yet Newton was right – by mastering the fluidity of the atom we have been able to change the most humble of materials into more wealth and power that we could ever have predicted in our wildest dreams.

We are almost at the end of our educational journey, but there is time yet to investigate some of the challenges facing science as it moves into the twenty-first century. What have we learned from our past, and what remains for us in the years to come? What gifts and challenges has the scientific endeavour provided for our lives today? It is to these questions that we turn next.
Journey’s End

“To explain all nature is too difficult a task for any one man or even for any one age. ’Tis much better to do a little with certainty, & leave the rest for others that come after you, than to explain all things by conjecture without making sure of any thing.”

Newton

Isaac Newton was once asked to describe how he viewed his own extraordinary accomplishments and, in a rare moment of modesty, he famously replied that he was “like a boy playing on the sea-shore, diverting myself now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.” It is a strikingly self-deprecating comment to come from a man who was usually so prone to self-aggrandizing arrogance.

I don’t think that it’s an exaggeration to say that most scientists today still feel the way Newton did three hundred years ago – perhaps far more so. Despite the staggering progress that we have made since Newton’s time, the mystery of the Universe, if anything, seems to have increased. That’s not to say that we haven’t learned anything new – on the contrary, these few centuries have brought with them a vast wealth of knowledge across all branches of learning. What I’m claiming is that, although our knowledge has increased enormously since the time of Newton, that same knowledge has brought with it the realisation that the Universe is actually vastly more complex and diverse than we had ever imagined. And as the mystery of the Universe has been revealed and the difficulty of exploring it has become ever greater, each step of
our intellectual journey has required more elaborate and expensive tools to answer the increasingly fundamental questions that we have uncovered.

So what progress have we actually made since Newton breathed his last? Can we say, on balance, whether or not the last three hundred years of progress have left us in a better or worse condition than the world that he left behind? And, perhaps more importantly for us, now that we join him on the journey of discovery from this point forward and neither we nor Newton know what lies ahead, which changes will the scientific endeavour bring us in the centuries to come and what can we do to ensure it continues to deliver on its grand promises?

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In the last chapter, I suggested that the deepest questions confronting us in the 21st Century will concern how we, as a civilisation, approach the acquisition of knowledge. Given the extraordinary scope of the discoveries of modern science, might we conclude that we are learning too quickly? If we should ever want proof of the power of human ingenuity, we need look no further than the extraordinary growth of the Information Age and the broad social changes that it has fostered within a generation. If we extrapolate into the future the progress made just in the last two short decades, it is undeniable that the world of 2100 will be almost unrecognisably different to the one we know today.

However, one thing of which we can be absolutely certain about future centuries is that they will feature increasingly profound scientific discoveries that will continue to shake our moral sense as much as they excite our collective imagination. Does that necessarily imply that we should temper our inquiry so that society can catch up with technology and debate these deep moral questions in appropriate depth? Should we, in effect, deliberately blunt our scalpel?

Alfred, Lord Tennyson (1809 – 1892), sits alongside Newton in the ante-chapel of Trinity College, Cambridge. In 1842, almost exactly two
hundred years after the birth of Isaac Newton, he published a book of poetry including one of his most celebrated works, “Locksley Hall”. In it, a lone soldier stumbles across his childhood home, and remembers the joys of youth and the pain of lost love. Towards the end of the poem, he recalls the land where he was born and its primitive ways, yearning for them at first, but then realising that the discoveries of the intervening years have brought with them a far greater prize. Progress, he concludes, is a valuable achievement and a noble goal worth pursuing.

The poem is a work of great poignancy because it summarises why the story of scientific endeavour needs to be told. Nostalgia will always draw us back towards our youth, but the eventual joy of progress is far more rewarding. In Tennyson’s words:

Yet I doubt not thro' the ages one increasing purpose runs,
And the thoughts of men are widen'd with the process of the suns.
...
Not in vain the distance beacons. Forward, forward let us range,
Let the great world spin for ever down the ringing grooves of change.

Though some people around the world still attempt to shield themselves from the accumulated wealth of human understanding, most realise that the unhindered access to knowledge is a vital cornerstone of modern civilisation. Yet the argument is often made that our inquisitive investigation into the nature of the Universe is doing more harm than good – especially if one accidentally reads the tabloid press. The modern world does appear uniquely stressful and unpleasant: Children today are forced to grow up too quickly without enjoying the pleasures of youth; our working hours eat up all our free time; warfare rages out of control around the globe; a plethora of deadly diseases threatens our every waking hour.
Except that everything I just said is exactly false – at least in the rich, first-world nations where these complaints are most commonly made. Let’s look at them in turn.

Children today have lives of extraordinary leisure compared to those of their grandparents or great-grandparents – and certainly their lot is far superior to that of any more distant generations. For centuries, children had been forced down damp, dark tunnels under the Earth, digging out dirty black coal and coating their lungs in its suffocating dust. Countless thousands – millions maybe – have toiled and perished in forgotten underground prisons just so that human beings could light their homes and cook their dinners. Countless more were forced to work in cotton mills from the age of twelve. Widespread child labour fuelled the Industrial revolution, but modern technology has allowed us to do away with all of this, and given us ways to generate limitless power cheaply and cleanly.

Infant mortality in the Western world is now slightly above four deaths per thousand live births, which is two-and-a-half times lower than it was even when I was born (and I’m not that old). In the late 19th Century, fully fifteen percent of babies born in England would be dead before their first birthday. That’s roughly four children in each primary school class today who wouldn’t have made it if they had been born a century earlier. Untold millions of lives have been saved, and are being saved as we speak, by the application of scientific methods to develop revolutionary new medicines and medical techniques such as vaccinations for a wide range of hideous diseases, and life support for babies born prematurely.

So that’s childhood – but what about working hours? In the UK, the 1833 Factory Act responded to the working conditions in cotton mills, and decided that it would be a good idea to restrict working hours for children to 12 hours per day. It wasn’t really enforced, of course. In the 1860s, the work week was extended from 58 to 60 hours. Before the Industrial revolution, when Britain was mainly an agrarian economy,
children and adults would be required to work potentially unlimited hours to provide enough food for the family to eat. Though it may not seem like it, replacing tedious and dangerous menial tasks with technology has hugely reduced the proportion of our lives spent at work. There will always be a minority working in highly demanding industries like law, finance and consulting, who may still work eighty, ninety or more hours per week, but at least that is now their choice and they are adequately rewarded for their efforts.

True, scientific advances might not yet have provided a robot butler to every household, but the countless labour-saving devices that we all enjoy in our homes free up many hours a week to spend on leisure and relaxation. For most of human history, housework was seen as the woman’s domain – and it was often an extraordinarily time-consuming responsibility. The rise of automation has surely contributed to the feminist cause, making it far easier for women to enter the workplace and pursue careers of their own after thousands of years of repression.

But surely, given the vast expense that all governments pour into military research and development, I must at least agree that warfare is getting worse nowadays? Well, actually no. Not even close. Harvard Psychologist Steven Pinker has already done much of the hard work on this topic in his book *The Better Angels of our Nature*, and the numbers are striking – in the 1950s, 65,000 people per year were dying in interstate wars. Today it’s fewer than 2,000. That’s still 2,000 too many, but at least the trend is in the right direction.

If you look at pre-technological societies like the Jivaro or Yanomamö of South America, half of all males can expect to die in warfare.99 HALF! Think about that for a while. If you are a man then flip a coin – if it comes up heads then you will die a brutal, violent death. If you are a woman, then think about the two men closest to you – perhaps your father and husband. One of those two men will probably be hacked to

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99 See the works of Napoleon Chagnon with the Yanomamö, published in the late 1960s and early 1970s.

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pieces by a murderer’s blade, possibly before your eyes. And your own fate – well you can probably guess. This is the nature of the ‘idyllic natural state’ from which we have progressed – and I make no apologies to cultural relativists who insist that our own society is no way objectively ‘better’ than one of such pervasive barbarism; anyone proposing such undeniable nonsense is not, I’m afraid, inhabiting reality.

But what about Hiroshima and Nagasaki? In the last chapter I covered the extraordinary devastation inflicted on Japan by the atomic weapons dropped in 1945. Well, as I mentioned earlier, the death toll from each of those two catastrophic events was actually lower than that caused by the conventional fire-bombing raid on Tokyo just three weeks before Hiroshima was destroyed. And as you are well aware, since Nagasaki – seventy years ago – atomic weapons have never again been used in anger. In fact, the seventy subsequent years of peace in Western Europe suggest that, for the first time in human history, the goal of a future without warfare might be achievable within our lifetimes. The abundant resources that science has given us, coupled with the enormous economic and military costs of aggression, mean that there is no longer any incentive for prosperous western nations to fight.

So what about non-war violence? Well, repeated studies show that the trend of violence in our culture is rapidly decreasing. We (at least in the developed world, though the trend holds for most places) are now living in the safest, most comfortable and least threatened time in the history of our species. The chance of us dying through violence is lower now than it has ever been. Not just a fraction lower, but orders of magnitude lower. According to criminologist Manuel Eisner, homicide rates in Europe have dropped from around thirty per 100,000 people per year in the 14th Century, to less than one per 100,000 people per year today.100 Imagine what the newspapers would look like if every one-off stabbing

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reported on the front pages was instead a mass slaughter of dozens. That’s what we’ve come from within recent recorded history.

There are many reasons, of course, why rates of violence have so dramatically fallen in Western nations. Though amongst those reasons, scientific progress seems responsible for several of the most plausible, including the improvement of forensic detective techniques and the ability to share information with law enforcement agencies rapidly across the globe. In addition to that, the rise of rapid long-range communication has allowed us access to a broader range of perspectives and encouraged tolerance through familiarity; and widespread commerce, powered by improvements to navigation and communication technology, has driven the mutual benefits of economic cooperation over territorial aggression. And of course, as one of the prime causes of violent crime is physical necessity, the fact that scientific advances have brought us lives of plenty, at least compared to our historical neighbours, means that there is no longer much call for the criminal to ply his trade.

Finally, if you think the “increased risk of disease” argument works, then you ought to go back and re-read the chapter on germ theory. We have completely eradicated entire diseases from the Earth forever, ending some of the most terrifying scourges ever to afflict humanity. Though work still remains to be done in the developing world, we have effectively rid humanity of the threat of smallpox, typhus, cholera, bubonic plague, polio and many more. These were diseases that, even during Newton’s life, brought entire countries to their knees – and now they are relics of history.

Occasionally irresponsible writers dwell on the fact that cancer incidence rates are climbing higher year by year, and for some reason they manage to offload the blame on modern society. Certainly some modern dietary and lifestyle choices, such as smoking and excessive unprotected sunbathing, do contribute significantly to cancer incidence rates, but that can hardly be blamed on scientific progress – after all, if
you want to buy proven carcinogens, set fire to them and inhale the results, then that’s your own lookout. However, though the incidence of cancer is increasing, the mortality rate is dropping, and has been doing so steadily for decades. That is to say, more people are getting cancer, but far fewer are dying of it.

In reality, the reason why cancer is still so deadly is that it’s one of the last remaining conditions that we can’t yet reliably cure. People die of cancer because they are surviving everything else. We have cures to all of the deadly plagues that killed and maimed millions within the last century, and medical treatments allow us to live far longer than any generation before us. The only thing, I believe, that stops us from understanding the extraordinary fortune that we have to be living in the 21st Century is a shameful ignorance of history.

I think it is clear that, as Science has provided us with more knowledge, some people have used that knowledge to beat us down and impoverish the state of humanity. But I think it is also clear that many others have used that same knowledge to lift us up. And it is abundantly obvious from even a casual glance at history that the ‘lifters’ are winning.

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I hope that I have at least sketched the outline of a case that, no matter how it may occasionally seem to us today, the progress of society over the last three centuries, largely driven by scientific advances like those we have met in this book, has significantly improved the condition of the human race. So the remaining task – the last phase of Newton’s education – is one in which we ourselves must join him in ignorance as we ask what the future holds for our species, and investigate what we can do, as conscientious citizens of a global civilisation, to ensure that the rest of the world gets to follow us on this path of progress.

Those of you who are old enough to remember a world before mobile phones may remember the protocol we had to go through when
arranging to meet a friend at a distant location. I remember planning everything several days ahead, organising specific locations in which to meet, back-up locations in case the first location was not available, checkpoints in case one of us was excessively delayed. These issues will seem alien to anyone born since the mid-1980s, but that is a striking indication of how fast society can change when technology permits. The effect of the first radio and telephonic communications caused a very similar, equally significant and impactful shift in how human societies operated in the nineteenth century too.

So what comparable wonders await us in the future? What technological advances of which we are currently entirely ignorant will render the world of tomorrow as incomprehensible to me and you as our world might have been to Isaac Newton before we so carefully explained it all to him?

We can at least guess at some of this by extrapolating current trends, but then there is no way whatsoever to know which remarkable discoveries will spring unexpectedly from some completely unpredictable area of research. After all, almost nobody saw the Internet coming, and even after it began to take shape in the 1980s, still very few people predicted how important it would eventually become. That’s part of the excitement of the modern world. But let’s not dodge the realisation that the extraordinary technologies poised to revolutionise the remainder of our lifetimes will come about not because of wishful thinking, intuition or dogma – they will arise instead through the process of careful scientific investigation.

Predicting the future is not an easy task. Some changes are obvious – like the steadily rising global population and the challenges that will bring; the threat of global warming and the increasingly frantic goal to divest ourselves of all polluting sources of energy generation; the eventual depletion of fossil fuels and the enormous cultural and economic shifts that will create. Yet there will be many remarkable
breakthroughs that, as history has shown, we humans are terrible at predicting.

My favourite example of this is an article in the magazine *Mechanix Illustrated*, published in November 1968. The magazine had just celebrated its 40th Anniversary, and the author James R. Berry wanted to look forward another forty years to predict what the world would be like in the heady futuristic utopia of 2008. His vision was striking, and he got a lot absolutely right – with giant interactive televisions in most homes, many systems being electronically controlled, online education, electronic shopping from the comfort of your living room and digital newspapers. He also foresaw computer-piloted cars, perhaps slightly optimistically, though I hope that the next few years should also prove that prediction right. However, there were also some spectacular misses, with cares travelling at 250 mph, travellator-style moving pavements alongside roads and entire cities bizarrely encased in giant glass bubbles – presumably at extraordinary cost, and for a reason that has never quite made any sense to me. Intercontinental transport, in his view, would be by rocket, robots would perform menial household chores and we would all take regular holidays in space.

Yet the most striking error for me was nothing to do with technological advancement, it was a social one. “Other conveniences ease kitchen work,” predicts the article, triumphantly. “The housewife simply determines in advance her menus for the week, then slips pre-packaged meals into the freezer and lets the automatic food utility do the rest.” The error is striking because the author had foreseen this extraordinary Jules-Verne-esque world with computers running the show, undersea hotels and “intelligence pills”, but yet had completely missed a relatively mundane and obvious social shift such as the rejection of traditional gender roles in modern relationships. The futurist of 1968 was able to envision entire cities sealed into climate-controlled bubbles, but couldn’t conceive of the possibility that *people themselves* might change.

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In many of the stories in this book, I freely admit, I have been guilty of ascribing progress too readily to a handful of key individuals rather than acknowledging the work of the multitudes of able researchers who have supported those same pioneers and helped to develop their initial sparks of genius. Yet Science is a gradual process, always seeking to increase our understanding by small steps, in the direction of greater knowledge and a more complete and trustworthy picture of the world around us. A scientific discovery, once published, should survive until disproved.

One of the most famous centres of learning in the history of science was the great library of Alexandria – one of the Seven Wonders of the Ancient World. The various owners of the library had, over many years, gathered together the largest collection of documents ever assembled before the advent of the printing press, perhaps containing up to half a million individual scrolls recording tens of thousands of different works by the greatest minds of the time. There were tracts on mathematics, philosophy, astronomy, medicine and warfare. There were great plays, poems, letters and speeches by the finest orators of history. It is the sort of place that makes modern-day classicists green with envy.

History is unclear about exactly when and why the library fell, but it seems that the most likely date was 391AD, after the Roman Emperor Theodosius I made pagan religion illegal and ordered that all the temples to the pagan Gods be destroyed, including those in Alexandria. As the library itself was contained within such a temple, it is likely that it was razed along with the complex around it. Yet probably the library had been falling into disrepair for some time before that date, with successive Roman Emperors removing and disposing of works that they found distasteful. Even after the fall of Rome, religious powers throughout history, from the early Christians in the 4th and 5th centuries to the Islamic rulers in the 7th century, deemed much of the surviving works to be heretical or immoral, and consigned them to the flames.
It is impossible to tell what cultural treasures have been lost forever as a result of the destruction of the Great Library. Yet it is far from the only example of such extraordinary cultural and intellectual annihilation. Just imagine how many great scientists, original thinkers, skilled playwrights and engineers there have been throughout the course of human history, whose works are entirely lost to us today either because of carelessness, misfortune, contrary fashions, or active censorship. We will never know those works, and our civilisation is forever impoverished through the loss of the irreplaceable genius of those unknown human minds.

The Information age in which we now live has revolutionised the process of scientific research and has generated staggering benefits for the human race. The creation of a free, distributed platform for the sharing of information - the Internet - has provided humanity with something far more valuable than even the Alexandrian Library. We have finally learned that the way to benefit most from knowledge is not to keep it securely locked up in a dusty vault, but to distribute it as freely and widely as possible. This culture of sharing information across social and national borders fosters understanding and encourages us to build a common cause with our fellow human beings. And, perhaps even more importantly, it ensures that we will never again lose any important thought or valuable insight so long as someone somewhere considers it important enough to share with others. Thanks to this extraordinary new technology, the products of the human mind can be safeguarded for eternity, for everyone to enjoy and for the benefit of us all.

To illustrate how far we have come, we need not cast our minds back too far. I distinctly remember many occasions as a child when our class teacher would give us all research assignments to carry out at home. Usually we were instructed to learn all about some obscure country, or perhaps a largely-ignored historical event. Each of us would be given a different topic and told to report back to the class the following week, sharing everything we had learned. I remember these assignments with
a mix of excitement and trepidation. It was always fun learning about new and exotic places and discovering things that nobody else in my class would know. But it was also a source of real anxiety because if I couldn’t find anything out about my chosen topic then I would get a terrible grade. This is where I start confusing anyone born since the late 1980s – what I am about to say will seem as alien to you as steam engines and leech therapy.

Completing these homework assignments usually came down one of three possible routes. Imagine you were assigned to research the geography and politics of a distant country, for example Mongolia. The first option was always to ascertain whether or not your parents knew the answers. A long shot, admittedly, but worth a try. Perhaps you had been born to career diplomats or geography professors, but most of us were not. If you got no luck there, then the next possibility was to hope that those same parents at least possessed an encyclopedia\textsuperscript{101} in which you could look up the answers for yourself. Some families had them, but many didn’t, and often they were so out-of-date as to make them useless for the task at hand. Still nothing? Then there was just one possibility remaining, and it was the last hope - you had to rely on there being a decent library\textsuperscript{102} nearby and beg your parents to drive you there. Once you arrived, it would often take hours of diligent searching to find anything of relevance.

If those three avenues were all closed to you, then I’m afraid you were totally out of luck; there was no way you could ever find out what you needed to know. The information was not available to you and there was nothing you could do about it. With the exception of the last two decades, this is how it has been for the entirety of human history.

\textsuperscript{101} For those born since the late 1980s, an encyclopedia is like a giant paper version of Wikipedia, but with much less information, significantly more out-of-date, and without the animations and clickable links. And it took up an entire bookshelf. There were salesmen employed to travel door-to-door and sell these colossal tomes to people for equally colossal sums of money.

\textsuperscript{102} For those born since 2000, a library was a large building full of books, which you could borrow free of charge for a limited period.
We have learned to take it for granted so quickly, but nowadays when I search the Internet for the geography and politics of Mongolia, I turn up a quarter of a billion pages of information in 0.62 seconds. I can learn all about their flag, their national anthem, their demographic statistics, their tourist highlights and a clickable, zoomable map of the entire country. Some of these pages are in foreign languages which are instantly translated for me when I click on them. All of this is completely free and available to me at any time I wish to look it up from the warmth and privacy of my office. If a fact is known by more than a handful of people worldwide, then nowadays it is knowable by anyone with an Internet connection. This is a staggering, breathtaking, epoch-defining social advance. I don’t believe that any country on Earth has yet grasped just how world-changingly immense this information revolution truly is.

Yet perhaps this freedom of knowledge hides a new and malicious threat. I have assumed so far that the ready availability of information on any topic would be a force for good in the world, yet reality is often rather more nuanced. As with so many other advances, there is good and bad to be considered here.

I firmly believe that the Internet – this extraordinary human accomplishment – is the greatest power for peace and prosperity ever created. Yet it is also a double-edged sword. Just as the first telephones allowed distant friends and relatives to communicate instantly across continents and oceans, that same technology was also used to coordinate warfare and to spread lies and deceit. So it is with the Internet. The same infrastructure that gives us vast online encyclopaedias, instant global news reports and cheap online shopping, also provides a haven for fraudsters, violent ideologies and organised crime.

As the twentieth century showed perhaps more than any other, information can be used for good or evil. Quite apart from the
propagation of lies, the Internet also gives us the possibility to spread *misleading truths*, and they are even more damaging. A lie can be disproved, but a misleading truth cannot be disproved, and continues to mislead until the listener is provided with a more complete picture of reality.

What do I mean by a misleading truth? Let’s look at an example to illustrate this problem. Imagine I wanted to tell you about my favourite sporting team. Let’s also suggest that you are from a foreign country without any knowledge of this team or the sport that it plays. And let’s say I wanted to give you the impression that my favourite team was the greatest team in the world and, most importantly, I wanted to accomplish this without lying. How would I achieve this seemingly impossible task?

Well, first of all I would show you many videos of the games that my favourite team comfortably won, I would show you the trophies they lifted, the players they had on the “greatest ever” lists, the amazing goals, the extraordinary comebacks and the stupendous victories against powerful opponents. I would provide you with biased quotes and newspaper headlines, and play the triumphant sound of my team’s jubilant fans singing proudly from a packed-out home stadium.

After viewing all of those videos and reading those carefully-selected statistics, you might indeed be forgiven for coming away with the opinion that the team I supported was in fact the greatest ever. Everything I told you about my team might have been absolutely true, yet the opinion you gained from it was probably completely false. Why? Because I showed you only one side of the story. I showed you all the wins, but none of the losses. I showed you the great players, but not the terrible ones. I showed you the trophies the team lifted, but not the competitions where they were knocked out in the first round.

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103 Maybe I should choose cricket?
This is how many delusions work, from scams such as “get rich quick” schemes, fad diets and ‘miracle cures’ to conspiracy theories, cultish religious movements and all manner of motivated denialism. People believe such stories for exactly the same reasons – they pick and choose from a subset of the evidence, and ignore the rest. Throw in a few extra lies (convincingly told) and it’s the recipe for an almost incurable delusion.

The Internet makes it much easier to find the information you want, but it doesn’t force you to find balanced counter-opinions for accuracy. In fact, it makes it easy to avoid contrary views that might shake your beliefs and it allows you to communicate exclusively with groups of like-minded individuals, mutually reinforcing your existing views without ever having to meet anyone who disagrees with you. In short, it permits people to live in Reality Bubbles where everything internally makes sense, but doesn’t necessarily correspond to the real world outside. Unfortunately our brains are not wired to seek the truth, only what seems to be true and feels comfortable to us.

So it cannot be denied that now, more than any time in history, the most important skill that any human being can learn is the ability to think well. The flood of information with which we are faced every day requires an accurate sense for discerning fact from fiction, and it’s a skill that remarkably few people ever consider important. Yet developing this way of thinking is absolutely vital if we are to make the most of the opportunities afforded to us by the Information Age, and avoid its many potential pitfalls.

In the 17th Century, scientists peering through the first microscopes realised to their great amazement that the environment in which we live is packed with countless trillions of microscopic creatures, bacteria and viruses, with the potential to do us harm. These were the cause of most transmittable diseases, responsible for billions of deaths since our species first arose. Indeed, the only reason why we humans are able to survive at all on this Earth is that we are defended by a highly
specialised, immensely powerful yet cleverly adaptive immune system that can learn to identify and eradicate infections before they take root. Despite the overwhelming number of microorganisms surrounding us at every moment, we very rarely fall ill and most illnesses that get past our initial defences can still be defeated in a matter of days or weeks.

It seems to me that our minds find themselves in an analogous state today, surrounded on all sides by staggering quantities of information that could influence our lives in potentially serious ways. Some of that information is valuable, some is worthless, yet some of it is actually dangerous. It could be argued that the repugnant anti-vaccination movement that has sprung up in the last decade or so across the developed world is no less of a virus than the common cold or flu. It spreads by contact with other carriers, takes hold by hitchhiking on some of the body’s most ancient mechanisms (in this case, the fact that our brains vastly overweight fears, even irrational ones, when making decisions, coupled with our suspicion of meddling with nature), and, most importantly, once you’ve caught it, you and those you love are at greatly increased risk of suffering from illness, disability or even death.

What we need when faced with such an onslaught is a trustworthy defence mechanism which sifts through the information all around us and learns how to sort nonsense from reality. If we fail at this task we may become overwhelmed with ‘mind infections’ against which we haven’t developed the necessary defences. Like H. G. Wells’ ill-fated Martian invaders in War of the Worlds, all our technological advancement will be worthless if we can’t accurately decide which information to believe.

The best way to safeguard the accumulated rewards of scientific progress is to build up a defence of rational, scientific skepticism. When our body is attacked by a bacterial infection, our immune system immediately recognises the impostor by its signature. The invading bacteria are then tagged, isolated and destroyed. Scientific skepticism is an immune system for our minds – it encourages us to challenge the
things we read and hear, to identify ideas that fit in with what we know about the Universe and to reject those ideas that do not.

The human brain is an extraordinary organ, but it has not evolved to thrive in the modern world. Opportunistic mental infections are assaulting our minds from all angles and our natural defences are largely useless. In fact, our brains often work against us by falling back too readily on instinct and primitive emotions that may not serve our best long-term interest. The practised Skeptic studies the ways in which our brains can deceive us and, combining this knowledge with the findings and methods of science and the principles of logical thought, learns how to approach novel claims in a way that protects her from misguided conclusions. An individual’s approach to novelty could be seen to lie on a scale from gullibility at one end to outright cynicism at the other. Skepticism is the healthy middle ground between the two. Always demand sufficient evidence for any claim, but always be ready to accept that same claim when the required evidence is provided.

The constituent techniques of science, which I have described over the course of this book, provide us with a rich toolset to set up our mental immune system. Scientific method insists that we look for evidence to support any claims, especially the extraordinary ones. It requires that we investigate arguments against our ideas just as thoroughly as we look for evidence in their favour. It acknowledges the limitations of the human brain and encourages us to remember that we can always be fooled. It forces us to separate the reality of what is true from the desire of what we would like to be true. It encourages the free and open discussion of all ideas so that discoveries can be shared and falsehoods exposed and rejected as rapidly as possible. And it demands a flexibility of mind that is willing to consider any opinion, yet will not cling on stubbornly to any belief once the evidence moves against it.

Building up our defences against pervasive and damaging falsehoods – not just pseudoscientific nonsense, but also more sinister racist, bigoted or extremist ideologies – seems to me to be a vital initiative for any
society that truly wishes to thrive in the Information age. I see it as no
different to the many other safety measures that we have put in place
over the years to protect our society from physical harm. In the UK
children are always taught to stop, look and listen whenever they cross
a road. Such a scheme was completely unnecessary for almost all the
history of civilisation, yet as the age of the automobile arrived and the
number of cars on our roads grew to dangerous levels, it became
necessary to prepare all members of society from an early age for the
perils that they would encounter. Nowadays all children in the
developed world are taught road safety, and it has become second
nature to look both ways before crossing a road. There are plenty of
other examples too – reminders to wear seatbelts in cars (“Clunk!
Click!”), or educational campaigns encouraging children not to talk to
strangers. Not to mention the many public health campaigns that
governments have launched over the years, or the widespread training
in First Aid and resuscitation techniques.

Thinking skeptically does not always come naturally – we all have to
work at it before we develop the necessary skills, but it is a habit that
will serve you well for your entire life. If we can build this skill into our
mental toolbox as a society then we will be able to stop worrying about
the drawbacks of the Information Age and capitalise on the benefits –
just like we did with the invention of steam power, electricity, the
telegraph, the telephone, the motor car, the airplane, the computer and
the mobile phone. Society seems to have an extraordinary elasticity
which never ceases to amaze me, and which we should never
underestimate, but it only works if we all do our part to support it.

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To tie up a few loose threads, let me restate that Science is a process for
determining how confident we can be about the truth or falsehood of
any testable proposition, but it doesn’t tell us what to do about that
knowledge. New facts don’t come with an instruction manual showing
how we should respond to them to best serve the public interest. Our
answers to the societal challenges raised by scientific progress will truly test us as a species, and we cannot expect that every year will be better than the last. But over time, as I hope this book has showed, the potential for scientific progress to uplift all of humanity is enormous.

We must accept that the Universe rarely gives us easy choices – nor should we want it to. Human beings need challenges; we need to search and strive towards a goal in order to feel alive. Many people believe that Science holds the answers, but I would like to propose that Science is itself the answer – it is the process of discovery that makes us so happy, not necessarily the destination. When we revisit Newton’s statue in Trinity College Chapel, looking eastwards towards the high altar, perhaps we now see not a sign of arrogance but rather a state of admiration. Newton believed in a deity that created this Universe with laws that could be dissected, understood and enjoyed. The more he studied that Universe, the more he came to respect it, and to realise that he was uncovering the pieces of something that was so much greater than himself. We may not share his particular religious views, but we can at least share his goal of understanding the Universe as clearly and as deeply as possible, and the joy that process brings.

Science is not just a means to an end, but it is the greatest adventure our species has ever undertaken. The inexorable rise to ever increasing standards of health and vitality, the gradual conquest of disease, the exploration of the cosmos, the eradication of warfare and the joining together of disparate cultures into one human civilisation – all of these grand projects owe their very existence, as well as their hope for success, on the scientific method and the efforts of many millions who work tirelessly to improve the human species for all who are lucky enough to be born into it.

Science will always strive to still greater and more empowering goals, and in doing so it will not only provide us with an endless stream of material possessions, but it will deliver new and illuminating vistas of
the Universe around us, new perspectives on the physical world, and even fresh understanding of what it is that makes us Human.

For a man with such unorthodox religious opinions, it was an extraordinary honour for Isaac Newton to find his final resting place in the nave of Westminster Abbey, London, amongst the greatest figures in English history. As with his statue in Trinity College Chapel, the grave contains a short inscription in Latin:

“*Hic depositum est, quod mortale fuit Isaaci Newtoni*”

Or, in English:

“*Here lies that which was mortal of Isaac Newton*”

Isaac Newton died just as the scientific age was beginning to flourish. Though he left many physical possessions behind him – his letters, books, belongings, and substantial financial wealth – the most important part of him, that which was *immortal* of Isaac Newton, was the spirit of rational empirical enquiry towards which he dedicated his life. That same spirit has brought us to the modern age, and continues to look away from the darkness of superstition and ignorance, towards a future overflowing with knowledge, and founded on the honest pursuit of true understanding.
Epilogue

The underlying theme of this entire book has, as I hope you’ve realised, been a celebration of the achievements of science and scientists throughout the ages since the birth of the modern scientific endeavour in the Middle Ages. I have used Isaac Newton as a baseline for this investigative journey because so much of this story began with him, although the constraints of space and the desire to weave a compelling narrative as well as to educate have forced me to simplify the picture and skip huge chunks of the story.

However, there is one profound common characteristic that I haven’t really dwelt upon at all, and it is so fundamental that it is shared by almost all of the great scientists we have met in this book – Isaac Newton, James Watt, Antoine Lavoisier, Charles Darwin, Louis Pasteur, Ernest Rutherford, Max Planck, Albert Einstein, Marie Curie, Edwin Hubble. There is one obvious property that they all share that neither you nor I can claim (at least not yet), and it’s actually remarkably relevant: They are all stone dead.

I appreciate that this may not immediately strike you as a particularly profound observation. That a man born in the 17th Century might not still be walking the Earth in the 21st probably does not, I admit, appear particularly newsworthy. Yet in this observation is hidden so much of the power and magnificence of the scientific process. In fact, it is of such profound importance that I might even consider it to be the underlying theme of this entire book – the most important fact that I have yet divulged. So why on Earth would I think that?

All the great discoveries that I have covered in this book, except perhaps for the very most recent ones right at the end, were made by people who are no longer alive. There is no way that we will ever be able to communicate directly with any of these leading figures, and they
will never themselves add another single letter to the unfolding book of science. Yet their influence is felt even today, through the ages, across oceans, in diverse languages, across faiths and political beliefs and bridging the social, linguistic, economical and technological gulf that separates our world from theirs. These great minds have left behind a valuable legacy which is, even now, being continuously woven into the evolving fabric of human society as we experience it in the 21st Century. We know their work, we understand their theories\textsuperscript{104}, and I’d like to think that, at least partly, we know them as human beings through their profound contributions to the human race.

Though all these heroes of the scientific revolution are no longer with us, we know about their invaluable contributions to the betterment of our species because their work was collected together, evaluated, verified and expanded. Taken as an ensemble, and when combined with all the contributions of their peers and contemporaries, these ideas built perhaps the most remarkable of all human endeavours in the history of our extraordinary species – the scientific understanding of the Universe.

Science is \textit{the} process – the \textit{only} process – by which we can \textit{reliably} examine the world around us. Other methods have been attempted from time to time, of course. Random guesswork, biased intuition, arbitrary superstition and unquestionable dogma have all played a substantial part in the history of the human race. In fact, they are still playing a fairly significant part today, much to the detriment of the peace, prosperity and happiness of our civilisation. But in terms of providing measurable results, Science is the only process that consistently delivers the goods. And perhaps more important than the demonstrable successes it brings, we also know \textit{why} it works so well.

It has been said, often in frustration and without merit, though occasionally with the infuriatingly incisive clarity that only a trained philosopher can achieve, that science is an imperfect discipline. And I don’t think that’s a particularly controversial view, much as I would

\textsuperscript{104} At least, some of us understand bits of them…
like it to be. After all, science is a process that relies on the whims of imperfect humans to execute it, and the list of known historical failures of the scientific process is both long and well publicised. It’s easy to emphasise those times when science has not served truth as efficiently as perhaps it could, but in doing so we risk forgetting the staggering and undeniable progress that it has empowered us to accomplish over those few centuries in which it has been practised in earnest. Science is, after all, the process that results when we as a human species attempt to learn about the world around us as accurately as possible, and to eliminate as much as possible all sources of error and bias. It is not an arbitrary set of prescriptions – it is the process that must be followed if we wish to have maximum confidence in our discoveries. And as we learn more about how we as a species can be fooled, we incorporate that knowledge into the scientific endeavour to ensure that the knowledge so gained is as accurate and reliable as possible.

I am reminded of a quote by one of my great heroes, the scientist and educator Martin Gardner.

“Biographical history, as taught in our public schools, is still largely a history of boneheads: ridiculous kings and queens, paranoid political leaders, compulsive voyagers, ignorant generals - the flotsam and jetsam of historical currents. The men who radically altered history, the great scientists and mathematicians, are seldom mentioned, if at all.”

Gardner was perhaps the first person to popularise the idea of recreational mathematics – a trend that no doubt contributed to the phenomenal success of number puzzles like SuDoku today. He also wrote “Fads and Fallacies in the Name of Science”, which was one of the first ever volumes to usher in the modern sceptical movement, and is a worthwhile read for anyone interested in scientific activism. I would argue that scientific activism – protecting the process of science

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and ensuring that it remains at the heart of the human endeavour – is a thoroughly worthwhile, even vital, activity, and I heartily recommend you to join in.

Given the extraordinary range and depth of scientific discoveries that have enriched our lives in countless many ways, even restricting our gaze to those discoveries covered in these few chapters, I would strongly suggest that the practice of science is something worth defending. I hope you would agree, and if you don’t then I can only decide at this point to part company from you with best wishes but without, I fear, the slightest mutual comprehension.

The fabled economics John Maynard Keynes gave an address to the Royal Society in 1942, the 300th anniversary of Newton’s birth. This was, of course, one of the darkest epochs in the history of our species, as the sickening violence of seemingly interminable warfare violated most of the developed world and the full might of science was being turned with inevitable rapidity and terror towards the task of murder and destruction. In these horrific, dark, demoralising days, what Keynes said resonates with a voice that is usually reserved for our most revered of poets.

“Newton was not the first of the age of reason. He was the last of the magicians, the last of the Babylonians and Sumerians, the last great mind that looked out on the visible and intellectual world with the same eyes as those who began to build our intellectual inheritance rather less than 10,000 years ago. Isaac Newton, a posthumous child born with no father on Christmas Day, 1642, was the last wonderchild to whom the Magi could do sincere and appropriate homage”\textsuperscript{106}

The age of human reason had begun with the Ancient Greeks, was continued by the Islamic philosophers as the Roman Empire crumbled,

\textsuperscript{106} John Maynard Keynes, Address to the Royal Society (1942)
but then stumbled into darkness for hundreds of years, except for the occasional light flickering in the shadows. Then a few brave and brilliant minds began to rekindle our human yearning for understanding. Sir Isaac Newton was one of those minds – perhaps the greatest – who first sought to illuminate the darkness and restore the flame of scientific enquiry to its rightful place of honour, never to be extinguished again. But he was by no means alone in this, and I hope I’ve shown in the pages leading up to this very point that the progress of Science depends not just on isolated genius, but also on the profound sacrifice and hard work of countless anonymous researchers, each brilliant in their own ways, but most sadly forgotten to any but the most dedicated collector of scientific trivia.

The discoveries that science has provided are now able to explain most of the commonplace elements of our world – those aspects that have puzzled humanity for millennia – and so we have begun to delve beyond the veil and into the murky, psychedelic world of the subatomic, where none but the most agile minds can venture. And now, lest we forget the aim of this entire discipline and discard it as something no longer relevant to the human race, we should cast our minds back in time to those many occasions where science began to tread new ground – with the microscope, telescope or glass prism – and we should recall the wonder and bemusement of those people then who wished so dearly to cling on to the old way of understanding that had served them so well for so many years. Yet time and again, science pressed forwards and now we, in our privileged position of hindsight, can no longer even conceive of an age where these epoch-defining discoveries were not considered as undeniable truth.

I have omitted many stories, and obscured a great deal in this book. No doubt I have enraged scholars of history, philosophy and science alike, and for that I apologise. I’m sure the angry letters I will doubtless receive will aptly chastise me for such an egregious mistake. Yet I have endeavoured to cover those moments in the history of science that most fascinate me, and which I think show the most substantial paradigm
shifts in terms of their effects on the minds of the general public. Ultimately though, my task was to create a narrative framework into which I could insert the most important lessons that we have learned from the history of human knowledge, and I hope that I have at least succeeded in that valuable effort. Some experts would no doubt argue for different discoveries, or different scientists within each chapter, but I made these choices and I stand by them all.

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Within modern society, at least in the West, certain schools of thought have recently fallen into the bizarre and irrational habit of implying, and occasionally even stating outright, that although Science creates undeniable advances, it also has a stultifying effect on human imagination and dignity. Science, so they claim, destroys in order to understand – in the infamous words of Keats, it seeks to “unweave a rainbow”\textsuperscript{107}. Isaac Newton thought differently. He found the pursuit of science to be the highest of any human activities, that it not only enriched the individual, but that it benefited all humankind. After all, by “unweaving” the rainbow, and understanding the spectral nature of light, Newton paved the way for our modern science of spectroscopy which has revealed to us the breathtaking vastness and beauty of our expanding Universe.

Indeed, the Newtonian view of knowledge is a noble viewpoint that stretches back to the Ancient Greeks, from whose tradition Newton drew his intellectual strength. The celebrated father of much Greek philosophy, Socrates, was quoted as saying, through the work of Diogenes Laertius

\textit{“There is only one good: knowledge, and one evil: ignorance.”}\textsuperscript{108}

\begin{itemize}
  \item John Keats, “Lamia” (1820)
  \item Diogenes Laertius, “Lives of Eminent Philosophers”
\end{itemize}
I don’t think I would go so far – faced by the immensity of the 21st century scientific corpus, one has no choice but to admit a profound ignorance in almost every field, and I don’t see how that could ever reasonably be overcome. In fact, to fail to admit one’s abject ignorance in the face of the colossal edifice of the modern scientific literature is a foolhardy arrogance. Our combined understanding of the Universe today is so extensive that one single human being has almost no chance of ever understanding more than a trivial portion of it. Yet I don’t really think that this was what Socrates could have been getting at – it would go against almost everything else he ever said on the topic. On the contrary, at least in my opinion, the real ‘evil’ is for us as a society not only to refuse to search after the true nature of the Universe, but also, having uncovered so many of its most fundamental secrets, to turn around and walk away as if nothing had happened – to retreat from the daylight, back into the dimly lit Platonic cave whence we have only recently emerged.

Knowledge is always greater than ignorance. I want to claim this as strongly as I am able. Knowledge is power – it is the only tool that separates modern day civilisation from our genetically indistinguishable hunter-gatherer ancestors of the Palaeolithic. Knowledge brings not only material wealth, health and comfort, but also the psychological well-being that comes from understanding one’s true place in the grand scheme of things; from understanding the intricate beauty of nature, and from learning to appreciate it on its deepest levels.

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Having made that point, it seems that our brief sojourn together is nearly at an end, and I might take this opportunity at long last to summarise what it is that I want you to take away from this rambling paean to Science.

Well, naturally I hope that I have conveyed something of my respect for Isaac Newton – if ever the epithet Great were deservedly applied to any
single human being, I am certain that Newton would be a worthy recipient. Though, if you recall, I mentioned in the introduction that this wasn’t primarily a book about Newton, much as the title seems to suggest otherwise. Far from it – this is a book about all of science, and in that vein I hope that I have engendered an equivalent respect for all the pioneers of science. And, perhaps even more importantly, I truly hope that I have helped to restore some respect for those who are not usually recorded in the annals of popular history.

We live in a privileged position in the midst of the human experiment. We are lucky enough to be alive, thanks to modern medicine, and we find ourselves protected against the diseases that have perhaps caused more human suffering than any other adversary since our species first arose on the African savanna. We are privileged to have been educated by the progress of scientific understanding and the social emancipation that it has supported. We are lucky enough to be able to travel, to communicate, to learn whatever we desire and to be able to look up any fragment from the human book of knowledge within seconds, using a device that fits in the palms of our hands. What, I wonder, would Isaac Newton have given for this extraordinary privilege? And how does that compare with your own assessment of these remarkable gifts? We have so very much for which to be grateful, and I find that we often forget just how fortunate we truly are, amongst the trials and tribulations of everyday life.

We are indeed the most fortunate human beings who have ever lived. And yet those who come after us have even more to look forward to – wonders that we can only dream of. We have access to all the eye-opening secrets that science has discovered and we have also, more importantly, inherited a view of the Universe that not only brings us much closer to reality than were any of our ancestors back to the beginning of time, but also brings us closer to each other. The challenges facing humanity in this newly unfolding century require unified, global responses, and this shared heritage of scientific
discovery gives us the foundation necessary on which to build a spectacular and abundant future for our species.

We are lucky enough to be standing on the shoulders of giants, and the truly joyous realisation, in my mind at least, is that there’s room enough for everyone. We are, I believe, morally obliged to bring all of humanity up here to enjoy with us the view that Sir Isaac Newton once glimpsed but which, thanks to the dedication and sacrifice made by the many extraordinary human beings whom I have introduced in this book, is now available for us all to savour and to enjoy.
Thank you for reading “Educating Newton”. This work is provided entirely for free and I encourage you to send it to anyone who might benefit from it. I assert my rights to be recognised as the author of this work in perpetuity and I do not grant permission to modify or abridge the work, to benefit financially from it, or offer it for sale without my express permission, or to attribute it to anyone other than me.

If you would like to learn more about science, please take a look at my online lectures at this location:

https://www.youtube.com/user/ColinFrayn