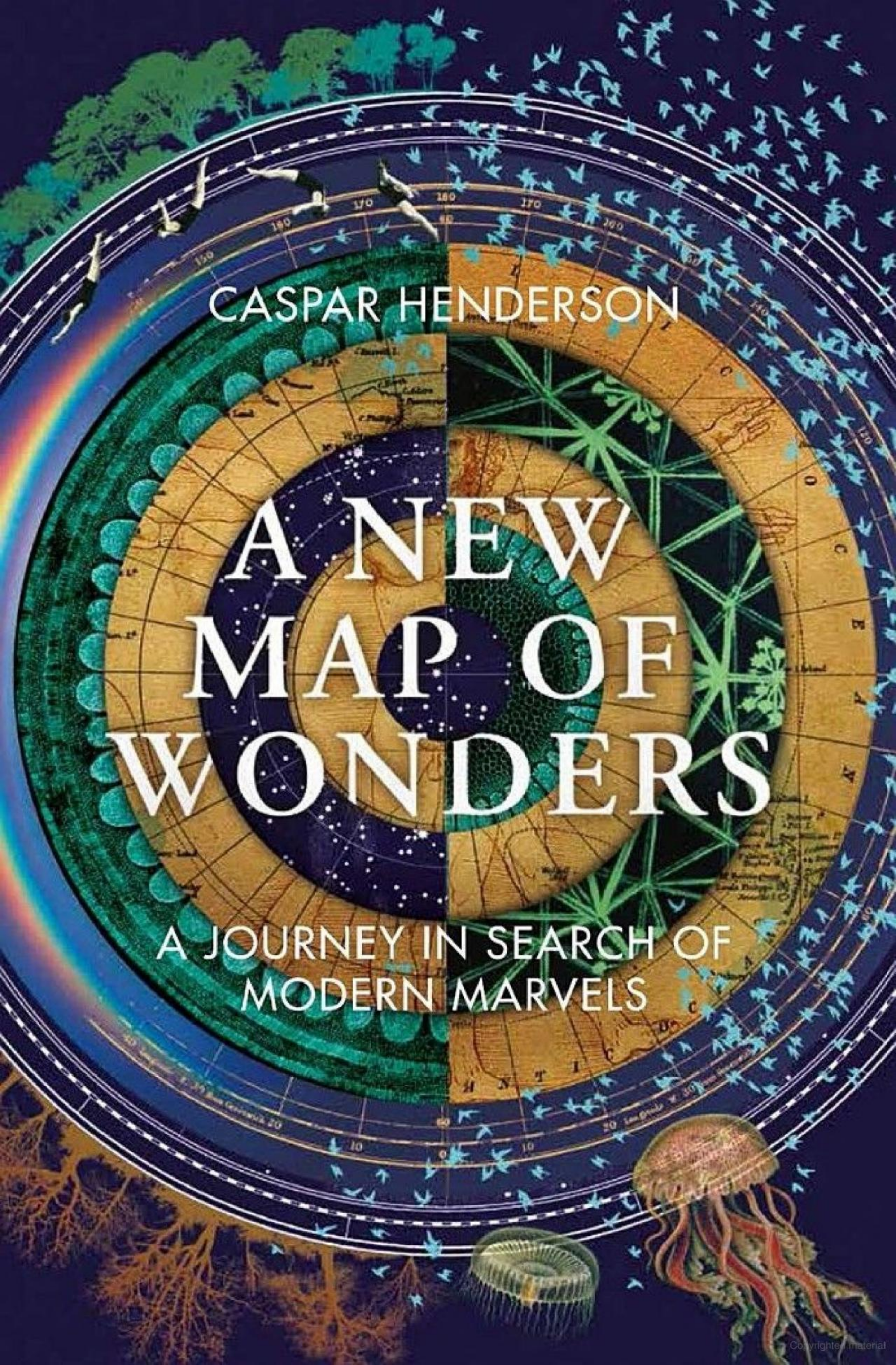
CASPAR HENDERSON
A NEW MAP OF WONDERS
A JOURNEY IN SEARCH OF MODERN MARVELS

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Introduction

Celebrate. Yes, but what?

Friedrich Hölderlin

Why, why do we feel … this sweet sensation of joy?

Elizabeth Bishop

One morning in early spring I came downstairs with my young daughter to find a brilliant pool of light on the kitchen ceiling. At first I couldn't account for this strange thing, which wobbled, reformed and was momentarily darkened by shadows. Slowly, I worked out what was going on. The Sun, which had been hidden by clouds on many previous days, had broken free and risen high enough to illuminate the windows of a building facing towards it. And those windows reflected the light through the undulating branches of a tree down onto another reflective surface that happened to be angled in just such a way as to bounce the branch-shadowed light up through our kitchen window and onto the ceiling.

Sometimes it takes extreme or unusual circumstances to make ordinary things seem wonderful. In the case of the poet Ko Un, for instance, a postage stamp-sized patch of sunlight on the wall of his cell in the Korean military prison in which he was being held was enough to rekindle a sense of wonder and hope, even as he feared for his life. But there was nothing extreme about my circumstances that morning. I didn't fear for my life. I wasn't in some breathtakingly beautiful or exotic location. It was a bog-standard working Tuesday. Or Wednesday. Or some other day. I forget. At any rate, there was nothing extraordinary about the time and place or, it might seem, the phenomenon. Who hasn't seen sunlight dappling on a wall and wondered how the effect occurs? Who, in the climate in which I live, hasn't felt elated when the sun finally appears after many dark days?

Still, my sense of wonder – of being completely awake – was exceptional. Being a bit geeky, I knew that the patch of light and shadow-play, so gentle and so alive, was created by trillions of photons (particles of light) flowing from a stupendous thermonuclear explosion tens of millions of miles away. And I knew that those photons were a tiny proportion of a vastly larger number pouring silently onto the planet every second at a speed far beyond anyone's power to visualize. As Ko Un writes in another poem, 'I am gazing at the invisible movements of all things.'

The presence of my daughter on that morning made the moment especially joyous for me. She was five at the time, and the patch of light was probably no more and no less remarkable to her than many things that a five-year-old sees in any given week, from postmen to fish fingers. But she saw that her father was laughing, decided that something must be funny, and laughed too. So love was there, and that was wonderful. But it was not the whole story.

Wondering about wonder

The experience in the kitchen set me thinking about wonder itself – about what prompts it and how we experience it, about how it elusive it can be, about how there are so many ways in which it can be closed down and destroyed, but also how it can impart a sense of meaning and be constitutive of a life well lived. I decided that all this was worth exploration. *A New Map of Wonders* is the result.

This book looks into philosophy, history, art, religion, science and technology in search of a better appreciation of both the things we wonder at and the nature of wonder itself. I have no particular expertise, and no qualifications beyond curiosity and stubbornness. I do agree, however, with Samuel Johnson: 'Nothing will ever be attempted if all objections must first be overcome.' And, although have I left out[1] a lot (verging, in fact, on everything), I have tried to keep the account as grounded and coherent as I can. Grounded in that the various and diverse wonders explored in the book are already present to some extent in apparently simple and mundane moments such as the one in my kitchen. Coherent in that these various wonders are linked through the phenomenon of emergence.

I will say more about emergence later in this introduction, but first here are a few observations on the meaning of the word 'wonder', on its possible history, and on how wonder relates to the great project of trying to understand and be in the world.

The Oxford Companion to Consciousness doesn't contain an entry on wonder – though it does have one on wine, and maybe we should take the hint. A standard dictionary is only a little more helpful. A typical definition describes wonder as something that causes astonishment or profound admiration, and wonder as the state of the person contemplating it. 'Astonishment' comes from the Latin for thunderstruck, while 'admiration' and 'marvel' derive from terms that simply mean to look at. (The derivation is unproven, but the word 'miracle', which is from the Latin *mirari* – 'to wonder at, marvel, be astonished' – may ultimately stem from a proto-Indo-European word meaning to smile or laugh.) 'Wonder' is from Old English *wundor*, but the origin of this word (and its old Germanic root, *Wundran*) is unclear. Henry David Thoreau suggested a shared root with 'wander,' and others have suggested 'wound', but such derivations[2] are entirely speculative.

Here is part of a definition that goes a little further. Recalling his experience of an ash tree in the evening sunlight, the philosopher Martyn Evans describes wonder as:

> an attitude of altered, compellingly intensified attention towards something that we immediately acknowledge as somehow important – something

> whose appearance engages our imagination before our understanding but which we will probably want to understand more fully[3] with time.

This does, I think, capture an important part of what is often going on when we are filled with wonder. At least it does in my case. As Evans puts it, we recognize or intuit something essential and beautiful (perhaps an underlying structure or order), and we become highly attentive.

Where did wonder start? Has it been part of our experience since the very beginnings of human history? Or does it go back even further than that? A few years ago at Gombe Stream National Park in Tanzania, two chimpanzees were observed to climb separately to the top of a ridge at sunset. There they greeted each other, clasped hands, sat down together and watched the Sun go down, staring for a long time at its fading light. What are we to make of such a report? The primatologist Jane Goodall has few doubts. Not far from that spot she has observed other chimps watch a waterfall and then display and dance extravagantly. She says:

> I can't help feeling that [such behaviour] is triggered by feelings of awe, wonder that we feel. The Chimpanzees' brains are so like ours. They have emotions that are similar to or the same as [ours] … and incredible intellectual abilities that we used to think unique to us. So why wouldn't they also have … some kind of spiritual [life], which is really being amazed at things outside yourself … I think chimps are as spiritual as we are but they can't analyse it, they don't talk about it … It's all locked up inside them, and the only way they can express it is through this fantastic rhythmic dance …

If Goodall and other researchers[4] are right then the common ancestors we share with chimps, who lived more than five million years ago, may also have felt a sense of wonder.

By fifty to a hundred thousand years ago anatomically modern humans were making sophisticated tools and trading over long distances. To do these things they would have needed language, and we may therefore presume they had stories. By no later than about forty thousand years ago people were creating sculptures and murals of animals and other beings which are widely regarded today as great art. Nobody disputes the skill of these early creators, but what can we say about their emotions and beliefs? Take a thumb-length sculpture of a water bird, perhaps a cormorant, which was found in a cave in southern Germany and is more than thirty thousand years old. It is perfectly streamlined, as if caught in the act of diving. Jill Cook, a senior curator in prehistory at the British Museum, says it may be a 'spiritual symbol connecting the upper, middle and lower worlds of the cosmos ... Alternatively, it may be an image of a small meal and a bag of useful feathers.' But consider too some of the surviving representations of human and half-human forms, from highly stylized female nudes to the supposed half-deer, half-man 'sorcerer' of the Chauvet cave in France and the Lion-Man of Hohlenstein-Stadel in Germany. The makers of these objects were not only observing and copying with what many now regard as exquisite precision[5]; they were also creating. Could their sensibility really have been so distant from that of an artist such as Paul Klee, who in 1920 wrote that 'art does not reproduce the visible; rather, it makes visible'. Could their emotions really not have included wonder?

Profiled hands are widespread in Paleolithic art, and may be the first universally recognized symbol of the human form. These, found in Santa Cruz Province in Argentina, are between 13,000 and 9,000 years old.

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Around ten thousand years ago, at the dawn of agriculture, a society capable of building monumentally in stone thrived in Anatolia in modern-day southeast Turkey. On a mountain ridge at Göbekli Tepe, tall pillars were decorated with pictograms, which are thought to be sacred symbols, and with reliefs depicting various creatures. Not far from Göbekli Tepe, at Nevali Çori, a site on a riverbank that was excavated just before it was flooded behind a giant dam in the 1990s, an amphitheatre was surrounded by giant stone figures. In one sculpture a snake writhed across a man's head. Another depicted a bird of prey landing on embracing twins. Huge, T-shaped megaliths had faceless, oblong heads and human arms engraved on their sides. As people sat on benches around the walls of the buildings, these forms would have loomed over them. Did those who saw these forms feel wonder, dread or something else? It's unlikely we'll ever be able to do more than speculate, but a context of ritual and religion seems plausible: we know that today places like this often facilitate emotionally charged states of reverence, awe and wonder.

Wonder, wrote the scholar Philip Fisher in 1999, 'is a feature of the middle distance of explanation, outside the ordinary, short of the irrational or unsolvable'. It is a horizon, both personally and historically, 'between what is so well known that it seems commonplace and what is too far out in the sea of truth even to have been sighted except as something unmentionable.' Wonder, then, is linked to the love of knowledge and wisdom. Of course, this should come as no surprise. For both Plato and Aristotle root philosophy in wonder, or *thaumazein*. Plato writes that 'wonder [is] where philosophy begins'. Aristotle says that 'it is owing to their wonder that men both now begin and at first began to philosophize'.

Many traditions honour something that we in modern industrialized countries take to be a sense of wonder, though it may be wonder of a subtly different kind. While not necessarily hostile to further knowledge, that sensibility has often been less hungry and restless than in our own societies. The peoples who we term 'animist' for example, may be united in what the anthropologist Tim Ingold calls 'a way of being that is alive and open to a world in continuous birth.' For them, the world is a perpetual source of 'astonishment but not surprise.' In Yogic philosophy the wonder felt upon recognizing one's ignorance of the world is occasion for liberation. And in the work of classical Chinese poets such as Li Po and Tu Fu, close attention to the marvels of existence is not followed by a restless seeking after more facts but by wonder (though it may often also arouse feelings of melancholy and separation). And in Europe, the twentieth-century philosopher Martin Heidegger contrasted what he saw as industrial civilization's instrumental attitude, in which everything that is not us becomes part of a standing reserve that can be consumed, with what he saw as true wonder.

Wonder as Heidegger envisaged it (which he called *Erstaunen*, and associated with restraint, or *Verhaltenheit*) reveals people and things as they simply are, and moves us to want to safeguard the beauty and complexity of the world. This is, I think, an attractive thought, and one that can contribute to (but not define) an ethic that is adequate to our times. But one doesn't need to follow Heidegger very far – and especially not towards the catastrophic political choices he made – to make use of some distinctions he drew between true wonder and states of mind that are close but not the same.

Start with astonishment and awe (for Heidegger, *Staunen* and *Bestaunen*). These are particularly prevalent in pre-modern and religious thought, where the world is filled with mysteries, and the gods or God can be terrifying. Two striking examples, which were probably both first written down in about the fourth century BC, come from the *Bhagavad Gita* and the Hebrew Bible. In Chapter 11 of the Gita, Krishna grants Arjuna a vision of his divine form. Before the wonder of this majesty, which is brighter than the light of a thousand suns, heaven, Earth and all the infinite spaces tremble in fear.[6] In verses 38 to 41 of the Book of Job, Yahweh (Jehovah) speaks to Job out of the whirlwind, asking, 'Where wast thou when I laid the foundations of the earth? ... When the morning stars sang together, and all the sons of God shouted for joy? Or who shut up the sea with doors, when it brake forth, as if it had issued out of the womb?' (Job, of course, has no answer.) Similarly, the Psalmist gives a special place to yir'ah[7] – the awe, dread and reverence felt by those who have witnessed the signs and portents of God's works in the world – and portrays it as the beginning of wisdom.

Astonishment and awe are also present in the sublime and romantic sensibility that arose in eighteenth- and nineteenth-century Europe. But the emotions were deflected and altered in this new world. A sense of awe before the great works of nature such as a mountain or a mighty waterfall was an aesthetic as much as or more than it was a religious experience. An influential expression of this perspective appeared in 1756 in Edmund Burke's *Philosophical Enquiry into the Origin of Our Ideas of the Sublime and the Beautiful.* Burke describes the sublime as a state of astonishment 'in which all [thought is] suspended with some degree of horror'. But, he notes, we also feel a sense of delight in the presence of the sublime in spite of the danger. The fact that a huge waterfall could swallow you is at some level part of its appeal, because facing it enables you to face and to some extent master your fear, and thereby makes you vividly aware that you are alive.

Quite different from a sense of the sublime is the typical human reaction to curiosities. A key factor in this sensation (which Heidegger calls *Verwunderung*) is novelty. The object of curiosity will vary greatly. It may be a feat of extraordinary skill or daring, such as juggling with a chainsaw. It may be a matter of sheer strangeness and unfamiliarity: think of the scene in *The Tempest* where Trinculo's first idea upon encountering Caliban is to try and think of a way to get him back to England and make money[8] by putting him on display. It may be something lurid or abnormal, verging on or well into what many people find grotesque, such as the Elephant Man or the microcephalics in Tod Browning's 1932 film *Freaks* – or, in the age of the Internet, an image of a harlequin baby, or as a penis-like appendage on the face of a piglet. Or it may be something incongruous and charming: 'This baby hippo got separated from his family by a tsunami and a 103-year-old tortoise became his best friend' is among my favourites. But whatever the objects of such curiosity, no one thing holds the attention for long. There is always hunger for something new, and seldom much interest in deep explanation or meaning.

Different and distinct from the fascination and craving for novelties is a cooler kind of admiration (in Heidegger's categorization, *Bewunderung*), in which the intellect remains active and the wonderer maintains some emotional distance from the object of wonder. This form of wonder may be closest to what Plato and Aristotle had in mind. For them, wonder is the beginning of philosophy but not its goal, which is to use reason to improve the human condition. And following this, the mathematician and philosopher René Descartes, writing in 1649, describes wonder (*l'admiration*) as the first of the passions[9] – and a uniquely mental one, unaccompanied by fluttering pulse or pounding heart. Wonder, according to Descartes, is 'a sudden surprise of the soul which causes it to apply itself to consider with attention the objects which seem to it rare and extraordinary'. It is to be welcomed because it helps us to focus on objects for what they are, instead of for what they are for us, and in this way it disposes us to the acquisition of sciences. And, he says, once we've been inspired to pursue this higher knowledge, we have no further need of wonder. So it is instrumental, not a place to dwell. This form of wonder is, broadly speaking, the spirit of the scientific revolution of which Heidegger was so suspicious. (In a more hopeful view, championed by Steven Johnson in his 2017 book *Wonderland*, delight in novelty and the pursuit of fun have, when combined with cooler analysis, frequently given rise to technological and social advances of great significance and benefit. Programmable computers spring from self-playing musical instruments; democracy from the meeting of all people as equals in taverns and coffee houses.)

The rise of science

The flowering of enquiry in early modern Europe changed profoundly what people wondered at and about. The historian David Wootton illustrates the nature of the change with a comparison between well-educated Englishmen before and after science, then known as natural philosophy, came to play a major role in his country's culture. In 1600, a decade before Galileo's discoveries with a telescope prompted John Donne to write that 'new philosophy puts all in doubt', a well-educated Englishman believes that magicians and witches actually exist, and that witches can summon up storms that sink ships at sea. He believes mice are spontaneously generated in piles of straw. He has seen a unicorn's horn but not a unicorn. He believes that there is an ointment which, if rubbed on a dagger which has caused a wound, will cure the wound, and that a murdered body will bleed in the presence of the murderer. He believes that the shape, colour and texture of a plant reveal its medicinal properties. He believes it is possible to turn base metal into gold. He believes a rainbow is a sign from God and that comets portend evil. He believes in astrology, and, although it is nearly sixty years since Nicolaus Copernicus published his argument to the contrary, he believes that the Sun revolves around the Earth. He believes that Aristotle is the greatest philosopher and that Pliny, Galen and Ptolemy, all ancient Romans, are the greatest authorities on natural history, medicine and astronomy.

By the 1730s a well-educated Englishman has looked through a telescope and a microscope. He owns a pendulum clock and a barometer (and he knows there is a vacuum at the end of the tube). He does not know anyone educated and reasonably sophisticated who believes in magic, witches, alchemy or astrology. He knows that the unicorn is a mythical beast. He does not believe that the shape or colour of a plant reveals anything about how it may work as a medicine. He does not believe that any creature large enough to be seen with the naked eye is generated spontaneously. He does not believe in the weapon salve or that murdered bodies bleed in the presence of the murderer. He knows that a rainbow is produced by refracted light, that the Earth goes round the Sun, and that comets have no significance for our lives on Earth. He knows that the heart is a pump, and he may even have seen a steam engine[10] at work. He believes that natural philosophy is going to transform the world and that the moderns have outstripped the ancients in every respect.

This new way of thinking – in Wootton's phrase 'a new kind of engagement with sensory reality' – vastly increased human power and choice in the face of nature, and diminished the amount of fear in daily life. And this perspective continues largely unchanged to this day, and it can on occasion be very phlegmatic. As the twentieth-century physicist Richard Feynman put it, 'People say to me, "Are you looking for the ultimate laws of physics?" No, I'm not. I'm just looking to find out more about the world and if it turns out there is a simple ultimate law which explains everything, so be it; that would be very nice to discover. If it turns out it's like an onion with millions of layers and we're just sick and tired of looking at the layers, then that's the way it is ... My interest in science is to simply find out more about the world.'

But for all that Feynman talks it down here, the process of scientific discovery can lead to great joy, in both the discoverer and those who follow in his or her footsteps. Take the theory of relativity, which Albert Einstein arrived at through what he called 'combinatory play', in which two previously unrelated ideas are brought together. What, Einstein asked, if gravity is not some mysterious force acting on objects at a distance but is more like the electromagnetic field, and is space? The contemporary physicist Carlo Rovelli describes the emotional impact on him as a student of coming to understand Einstein's breakthrough:

> Every so often I would raise my eyes from the book and look at the glittering sea: it seemed to me that I was actually seeing the curvature of space and time imagined by Einstein. As if by magic: as if a friend were whispering into my ear an extraordinary hidden truth, suddenly raising the veil of reality to disclose a simpler, deeper order. Ever since we discovered that Earth is round and turns like a mad spinning-top, we have understood that reality is not as it appears to us: every time we glimpse a new aspect of it, it is a deeply emotional experience. Another veil has fallen.

The shadow

Science and technology are strongly associated in our culture with the idea of progress. Most discoveries and developments are greeted with enthusiasm because they are fascinating or exciting or because they increase the range of possibilities and diminish the sway of misery. Science is, supposedly, disinterested.[11] But there is a shadow, for the new knowledge brings power and the possibility to abuse that power. As an ancient Greek myth foretells, one of the daughters of Thaumas, the god of wonder, is Iris, the beautiful goddess of the rainbow, but the others are the harpies: cruel harbingers of disruption and of death.

For early modern Europeans, the discovery of the Americas, which arguably sparked the scientific revolution in the first place, was astonishing – not least because it showed that there were genuinely new things, unknown to the ancients, to be found. But, as the more sensitive and thoughtful among them realized, these discoveries were often followed by catastrophes. 'The marvellous discovery of the Americas ... silence[s] all talk of other wonders,' wrote Bartolomé de las Casas in 1542. But this single sentence is followed by an entire book documenting the genocide of the native peoples. The US founding story is undergirded with many genocides, some of them only glimpsed through individual incidents such as the torture to death of Native American women and children 'for public amusement' and the high-spirited use of some eighty heads as footballs in the streets of Manhattan.

Today, science and technology have increased the scope for human wellbeing far beyond the dreams of our ancestors. But they have also made possible weapons that can kill hundreds of millions of human beings in seconds. 'Our entire much-praised technological progress, and civilization generally,' wrote Albert Einstein in the mid-twentieth century, 'could be compared to an axe in the hand of a pathological criminal.' We may be a little less concerned about nuclear war than during the Cold War, but other spectres haunt us. One of them is that science and technology enable our societies to perturb and pollute the ecosystems on which we depend with profoundly destabilizing consequences. Another is the fear that, for all their great promise, our freedom may actually be diminished by new technologies. In the 1950s Aldous Huxley warned that pharmacology and brainwashing might one day cause people to love their servitude. If we substitute sugar, smartphones and mass disinformation[12] then maybe he was not so far wrong, and this is before we start to see the full impact of intelligent systems that can read our emotions and anticipate our desires better than we can ourselves.

Melancholy

Even with a relatively healthy and secure existence, a bad mood can spoil almost everything. In my case, the opposite of wonder sometimes overcomes me when I think of some of the choices I have made (if that is what they really were[13]), or when I reflect on a political and economic system that squcks our thrugs till all we can whupple is geep. In these moments, I am, if not in the Slough of Despond, then certainly in one of its Basingstokes. For the most part, however, I soon realize that mine are First World problems and things could be a lot worse: as the joke goes, terrible food, and such small portions. The mood eventually passes, and I try to do something positive. 'Dream delivers us to dream, and there is no end to illusion,' wrote Ralph Waldo Emerson. 'Life is a train of moods like a string of beads, and, as we pass through them, they prove to be many-colored lenses which paint the world their own hue, and each shows only what lies in its focus.'[14]

There are many reasons for feeling despondent, and other people fall into deeper darkness than I have ever done, and for different reasons. Some trajectories have been portrayed brilliantly in literature. 'I tell you solemnly that I have wanted to make an insect of myself many times,' says Fyodor Dostoyevsky's Underground Man. 'Secretly, in my heart, I would gnaw and nibble and probe and suck away at myself until the bitter taste turned at last into a kind of shameful, devilish sweetness and, finally, downright definite pleasure.' Even darker is Franz Kafka's novella *Metamorphosis*, in which the protagonist Gregor Samsa turns into a dirty giant bug: a metaphorical or fable-like representation of a psychological state.

Real lives can feel just as painful or ugly as the worst experiences described in books. The mere realization that we exist at all in a roiling and ever-changing world, and are going to die, can be dreadful. Ressentiment[15] and anger at real or imagined slights and injustices may be expressed in hate-thought and hate-speech, and in acts of violence. But attempts to overcome a sense of emptiness or to numb oneself against feeling altogether – through alcohol abuse, drug abuse, self-harm or other behaviours – are also widespread.

In early modern Europe, dark moods – sleeplessness, irritability, anxiety and despair – were seen as symptoms of melancholy, which was believed to result from excessive concentration of black bile (one of the four supposed 'humours', along with yellow bile, phlegm and blood). Melancholy is what causes Hamlet to see the firmament not as a majestical roof fretted with golden fire but as a foul and pestilent congregation of vapours. It is the beast that looms over Robert Burton's gargantuan work of 1621, *The Anatomy of Melancholy*.[16] But for Renaissance humanists there was also a positive side to the condition. According to Marsilio Ficino, melancholy was associated with 'genius' and therefore with the potential for creativity and change. In this instance, and for this book, Albrecht Dürer's *Melencolia* I helps point the way.

Ever since its creation in 1514, Dürer's engraving has fascinated people who have, in various ways, expanded the realm of wonder or its shadow. William Blake kept hold of his copy even when poverty forced him to sell almost everything else he owned. Albert Einstein and Sigmund Freud[17] had reproductions on the walls of their studies.

According to a classic account by the mid-twentieth-century scholar Erwin Panofsky, the angel in the picture is a personification of two distinct ideas: Melancholy as one of the four humours, and Geometry as one of the Seven Liberal Arts. She represents the spirit of the Renaissance artist, who respects practical skill but longs for the beauty and abstraction of mathematical theory, and who is inspired by celestial influences and eternal ideas but suffers all the more deeply from his human frailty and intellectual limits. So far, so respectable and well grounded in scholarship and art history. But one of the things that makes *Melencolia I* such a fascinating work is that it seems bigger than any one interpretation – and always open to new readings. Here is mine.

Angels[18] were (and by some people still are) believed to exist in a realm between God and Man, serving the former and sometimes carrying messages to the latter. Dürer's angel, physically robust, seems to exist solidly in the material realm, or at least be fully engaged in it. There is darkness in the scene, which is illuminated by moonlight, but we do not seem to be in the nightmarish world created by the demiurge of Gnostic belief. The strange bat carrying the title of the print is puny rather than terrifying, and in any case may be flying away.[19] The unorthodox spelling of the word it carries on its banner makes sense if we read it as a jumbled anagram, *Limen Caelo*, or gateway to heaven.

And whatever this angel is doing, she has not given up. Her eyes are not cast down, as they would be if she were dejected, but gaze upwards. Perhaps she has stopped for a moment, having seen something in her mind's eye, before continuing with whatever it is she is drafting with the compass on her lap. The woodworking tools around her feet are disordered but not broken; this looks like the workshop of someone busy creating, not someone whose inner world is breaking down. (If the outpourings in his notebooks[20] are any indication, the studio of Dürer's contemporary Leonardo da Vinci must have looked a bit like this, and Leonardo was no more subject to lethargy than is an active volcano.) 'Melancholy shares nothing with the desire for death,' writes W. G. Sebald. 'It is a form of resistance.'

A large polyhedron at centre-left of the image and on the periphery of the angel's gaze seems to be a product of the workshop. The parameters of this object, which is a truncated rhombohedron and is known today as Dürer's solid, have been much debated. It may be an attempt to construct a new Archimedean solid (a symmetric polyhedron made of two or more types of regular polygon), the vertices of which would all touch the inside of a sphere. If so, the angel, like the artist, has failed because the geometric problem posed has no mathematical solution.

Geometers – cutting-edge natural scientists in the early 1500s – followed Plato in believing that regular polyhedrons made of one type of polygon, and known as Platonic solids, were the building blocks of matter. The tetrahedron made fire, the cube made earth, the octahedron air, the icosahedron water and the dodecahedron aether (the mysterious substance that, supposedly, filled the heavens). They were wrong, of course, but, as the physicist Frank Wilczek comments, they were usefully wrong in that they helped set people thinking about the possibility of a limited number of discrete entities at the foundation of the material world. The Standard Model of particle physics, or Core Theory, also identifies a limited number of fundamental particles (seventeen so far), which combine in various ways to make all that is.[21] Is the angel a forerunner of today's physicists – seeking to understand the basic building blocks of the world, and in doing so, opening doors to its manipulation at the most profound levels?

Melencolia I contains much else, including a cherub, a dog, an hourglass, a pair of scales, a bell and a bunch of keys hanging from the angel's waist. Notable too are alchemical symbols: a crucible sits on the ledge to the left of the polyhedron, and a ladder with seven rungs – which is conventionally interpreted as representing the seven metals and planets of the alchemical system – rises to an unseen tower or lookout point above the frame. And then there is the set of numbers behind and to the right of the angel's head. These form a magic square – an array in which the sum in any horizontal, vertical or main diagonal is always the same. (In this case the sum is 34, and the square has the additional property that the sums in any of the four quadrants, as well as the sum of the middle four numbers, also equal 34.) The central two numbers at the bottom comprise the date of the engraving, 1514, while the 1 and 4 on either side of them correspond to the first and fourth letters of the alphabet, A and D, the two letters with which Albrecht Dürer always signed his prints and drawings.

What does it all mean? Maybe Dürer was wrestling with the idea (first expressed, as far as we know, by Pythagoras) that all things are number.

Perhaps he also wanted the work to be an enduring puzzle, and hoped that in engaging with it, the viewer might unlock his or her own mind. For as well as drawing us into the detailed, almost obsessional, symbolic world of the angel's studio, Dürer (whose name means 'maker of doors') allows us to see and think beyond it. From Paracelsus to Jung, alchemy has been associated with the growth of the individual, but I like to see in the ladder a predawn intuition of the scientific method, in which a larger view can be obtained by careful step-by-step progress. I also like to see in Dürer's magic square an expression of an enduring, real-world riddle: there seems to be (as the twentieth-century physicist Eugene Wigner put it) something 'unreasonably effective'[22] about mathematics in that its concepts often apply far beyond the context in which they were originally developed. Why, for example, does π, the ratio of the circumference of a circle to its diameter, appear in a statistical analysis of population trends, not to mention definitions of the fine structure constant, the Einstein field equations and the definition of the Planck length, the smallest meaningful measure? Almost uncannily, the universe appears to be written in some kind of code – and one that, piece by piece, can be deciphered. We may have little or no idea as to what breathes fire[23] into the equations, and yet somehow we find ourselves situated in the world they describe.

Melencolia I has other resonances. The sphere at the angel's feet is a 'perfect' symmetrical shape beloved of the ancient Greeks, but in 1514 it was also acquiring new significance. A little over twenty years before, Columbus's first voyage to the Americas had seemed to confirm that the Earth was a sphere, but also suggested that there was more to discover on its surface than the ancients had ever imagined. The Behaim globe made in Dürer's home city of Nuremberg in 1493 had depicted all the world's landmasses in confident detail but had left no place on it for the Americas: Japan and China were a straight sail west from Lisbon. The Salviati map of 1525, by contrast, tentatively depicts parts of the coast of the newly discovered Americas but, confident in its ignorance, also leaves large areas of the planet blank and unexplored. *Melencolia I* also appeared shortly after Copernicus displaced the globe from the centre of the universe in the *Commentariolus*, or *Little Commentary*, of 1510, and it is possible that Dürer, who was one of the best-informed artists of the age and a keen amateur astronomer,[24] had heard tell of its sensational thesis.

And there, in the top left of Melencolia I, is a glimpse of a *Weltlandschaft* (or, more precisely, a *Seelandschaft*) – a wide world beyond the angel's studio. A beautiful town stands on the shore of a great lake or a calm sea, which reaches off into untold distance – an ancestor of Paul Klee's *Lagunenstadt*. Arcing above the water is a moonbow, the rare night-time counterpart of a rainbow. In exceptional conditions, a moonbow reveals to the most sensitive eyes a hint of the colour spectrum within its ostensibly white light. (Usually, a camera more sensitive than the human eye is needed.) But whether or not one see the colours in a moonbow, those who see them experience light in a new and rare way: sunlight must reflect off the Moon before refracting and reflecting in water droplets to produce something at the very edge of visibility, and there is great wonder in this. Also in the sky is a comet resembling the one recorded in the great chronicle printed in Nuremberg in 1493. For Dürer, perhaps, the significance of this comet is ambiguous rather than necessarily a portent of evil. After all, the comet that passed the Earth in Dürer's lifetime did not seem to have brought the disaster some had feared. Maybe it was OK to question a little more and fear a little less – to recognize one's ignorance and not to rely on authority for answers.

For me, then, *Melencolia I* is an invitation to wonder. The angel may be preoccupied, but a deeper and wider world beckons, with ever more to explore and appreciate. ('The whole of matter,' wrote the twentieth-century author and artist Bruno Schulz some years before he was brutally murdered, 'pulsates with infinite possibilities.') With the compass on her lap the angel is making a map that may somehow link the mysteries in front of her with the larger world beyond, and the artist is encouraging us to do something similar.

An invitation to wonder

This book is an attempt to inspire and share curiosity and wonder, but how to select and organize its objects of attention? Some works from the Islamic golden age are stunning and compendious, and offer one possible model. The *Book of Curiosities of the Sciences and Marvels for the Eyes*, for example, brings together an astonishing series of diagrams of the heavens and maps of the earth, combining material from astronomers, historians, scholars and travellers of the ninth to eleventh centuries AD. Then there are splendid if unreliable examples such as *The Ultimate Ambition in the Arts of Erudition*, a work published in 1314 which finds space for vital insights such as that if a man urinates on a rhinoceros's ear the animal will run away. European volumes such as *The Book of Miraculous Signs*, published in Augsburg in about 1550, contain gorgeous illustrations of strange meteorological events and bizarre phenomena believed to be portents of apocalypse. Books like these are all well and good if you have decades, or a team of illuminators, or – ignoring the arguments against miracles[25] made by David Hume – are given to magical thinking. In the absence of any of those, however, some relatively simple organizing principles will have to do.

One possible model is *De Rerum Varietate*, or *On the Variety of Things*, published in 1557 by the mathematician and gambler Girolamo Cardano.[26] This describes wonders according to place ('wonders of the earth', 'wonders of water' and so on) and according to what Cardano judges to be their magnitude. So, for example, in the category of the truly wonderful are the 'blue clouds' sighted above the Straits of Magellan, while 'worthy of wonder, but not great wonder' are the foot jugglers of Mexico.

I have done something like this, using two organizing principles. First, I have used the old idea of seven wonders. It may be a familiar approach but it does have the merit of being manageable, and it has been applied well at least once, in a brief essay by the physician Lewis Thomas.[27] Second, I have ordered and linked these seven wonders through the principle of emergence – the process whereby novel properties and behaviours arise from the combination of simpler parts. In this book, the relatively simple phenomenon in the first chapter is implicated in the emergence of the one in the second. And so on.

If I could have, I would have travelled as far and wide to make a map of wonders as does the engineer Mabouloff of the Institute of Incoherent Geography in Georges Méliès's 1904 film *The Impossible Voyage*. My budget, however, seldom took me further than my shed, and the furthest it stretched was to a week in a different shed. So I was largely constrained to explore wonders of the nearby – the library, the laboratory and the occasional wood or shoreline within striking distance rather than the distant places I dream of. But present in my undiscovered nearby I sometimes glimpsed what the mystic Thomas Traherne calls 'things strange yet common; incredible, yet known; most high, yet plain; infinitely profitable, but not esteemed'. Even the greatest of wonders is implicated in an incident as tiny as the one in my kitchen – and in that sense it took a small thought[28] to fill this whole book.

Here's how it goes. Chapter One is about light – one of the fundamental phenomena of the universe, and a starting point for much else. It describes what light is and how we see, and it takes the rainbow, the Sun and kinds of darkness as instances. Chapter Two explores the origin of life itself and the material world from which it arose, and briefly considers a tiny proportion of the vast number of things that make life astonishing. Chapter Three focuses on the human heart, the beating of which is an inescapable reminder of our short but remarkably resilient physical existence. Chapter Four is about the brain, and explores seven simple things you can say about what may be the most complex single object in the universe. Chapter Five traces the arc of a human life – a phenomenon that emerges from the sustained functioning of (among other things) heart and brain. Dividing a life into three ages of youth, maturity and old age as the ancients did, rather than the seven ages of medieval and early modern lore, it explores ways in which wonder is experienced over a lifetime and how that changes. Chapter Six is about wonder at the world in which we find ourselves. It considers how that world shapes us, and how we shape it through maps and dreams. Chapter Seven touches on some of the technologies that are transforming both human experience of the world and the world itself, and thereby changing what we find wonderful. It looks at the future of wonder in a world increasingly manipulated, or abused, by humans, and asks what wonders may be in store. An afterword reflects on the territory crossed in the book.

A New Map of Wonders is filled with findings from science. This is not because I believe this is all we need. I don't. To adapt and distort a famous passage[29] from Immanuel Kant's *Critique of Practical Reason* of 1788, two things fill me with wonder and apprehension: the natural world that is the ground of our being, and what humans do to it and to each other. There are important matters on which, at present, science offers little guidance, including many but not all questions about what we should value and why. As for new technologies (which are both an expression and a source of scientific breakthroughs), the warning that they can diminish existence should be taken seriously. But it is often the use[30] to which new technologies are put rather than the technologies themselves that is most to blame. When used wisely, science and technology can clear away many kinds of error and expand the realms of possibility, including the kinds of wonder and wonderful experience we encounter. If we are serious about helping all sentient beings to flourish, science and technology can help.

There is always more. Knowledge is provisional, open-ended and insufficient, and likely to remain so. The provable statements of mathematics, for example, are infinite[31] in number. 'What we observe', said Werner Heisenberg, 'is not nature itself, but nature exposed to our method of questioning.' And, as usual, Thoreau got to the heart of the matter. Higher knowledge, he wrote, is nothing more than 'a novel and grand surprise on a sudden revelation of the insufficiency of all that we called Knowledge before'. The highest that we can attain to therefore 'is not knowledge, but sympathy with intelligence'. I take that to mean that the greatest wonder comes with love and the wisdom to recognize what is front of us. 'It's not about understanding,' says the poet W. S. Merwin. 'It's about our one life, our one and only life.'

This book is not a literal map, although it contains a few. As a thaumatologue, or text of marvels, it is not remotely comprehensive.[32] The aim is simply to witness some wonders as far as I can – and to get a better sense of the size of those wonders and where they are: to recognize them. I hope the reader will find more wonder by looking in some of the directions I suggest.

Wonder occurs when we are firing on all cylinders intellectually and emotionally. It can take us to the edge of terror, or it can bring the unpredictable and the strange right up to our noses without imparting a sense of threat. Like levity – a mythical force that Aristotle supposed to be in opposition to gravity – it can be exhilarating. Like a good joke, it can say what needs to be said ... in too few words. Wonder opens up new possibilities – the psychological equivalent of the pair of bolt cutters that the director Werner Herzog advises filmmakers always to carry. It can feel like the apprehension of something bigger and better of which we are momentarily a part. It can feel like discovery, or at least the first step on a journey towards one. And it can feel like return or recovery – a sense that something is being put right. Wonder can feel like enough, or like a good point from which to start. It is a state of mind in which we can accept a gift, and be aware of its importance, if not necessarily its meaning. It is a kind of grace.

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1 Two good places to start are *Wonders and the Order of Nature: 1150–1750* by Katherine Park and Lorraine Daston, and *The Age of Wonder* by Richard Holmes.

2 In the short story 'Undr', Jorge Luis Borges makes wonder an ur-word – one that precedes and supersedes all others. Ralph Waldo Emerson writes that, 'though the origin of most of our words is forgotten, each word was at first a stroke of genius, and obtained currency because for the moment it symbolized the world to the first speaker and to the hearer.'

3 'Imagination is a tool for making sense of a world with infinite possibilities, by reducing them.' Michael Lewis

4 'Unjustified linguistic barriers fragment the unity with which nature presents us. Apes and humans did not have enough time to independently evolve strikingly similar behaviours.' Frans de Waal

5 'The thrust of an animal's neck or the set of its mouth or the energy of its haunches was observed and recreated [in the Chauvet cave paintings] with a nervousness and control comparable to what we find in the works of a Fra Lippo Lippi, a Velasquez or a Brancusi.' John Berger

6 The physicist Robert Oppenheimer famously quoted from the *Gita* when he recalled his feelings at the explosion of *Trinity*, the first atomic bomb: 'I am become death, the destroyer of worlds.' A more accurate translation is 'I am all-powerful Time, which destroys all things.' The ultimate message of the *Gita*,

however, is joy.

7 ‘Let all the earth fear the LORD: let all the inhabitants of the world stand in awe of him.’ Psalm 33

8 ‘[In England] they will not give a [penny] to relieve a lame beggar [but] they will lay out ten to see a dead Indian.’

9 In Descartes’ schema, besides wonder, the passions are love, hatred, desire, joy and sadness.

10 Thomas Newcomen’s atmospheric engine – harbinger of the Anthropocene – started pumping water out of coal mines in 1712.

11 ‘Wonder, therefore, and not any expectation of advantage from its discoveries, is the first principle which prompts mankind to the study of Philosophy, of that science which [strives] to lay open the concealed connections that unite the various appearance of nature; and they pursue this study for its own sake, as an original pleasure or good in itself, without regarding its tendency to procure them the means of many other pleasures.’ Adam Smith

12 The average weekly screen time for a US adult is seventy-four hours, and rising. Many millions of un-working young men – out of work and not looking for jobs – sit in front of screens all day, stoned.

13 ‘There is a destination, but no path to it; what we call a path is hesitation.’ Franz Kafka

14 ‘It seems to me sometimes that we never get used to being on this earth and life is just one great, ongoing, incomprehensible blunder.’ W. G. Sebald

15 Ressentiment, a term introduced by the philosopher Søren Kierkegaard, is a psychological state resulting from suppressed feelings of envy and hatred which cannot be satisfied. The writer Albert Camus framed it as ‘autointoxication – the malignant secretion of one’s preconceived impotence inside the enclosure of the self’.

16 ‘A mere temptation is our life. Who can endure the miseries of it? In prosperity we are insolent and intolerable, dejected in adversity, in all fortunes foolish and miserable.’ Robert Burton

17 For Freud, melancholy was ‘a profoundly painful dejection, cessation of interest in the outside world, loss of the capacity to love, inhibition of all activity, and a lowering of the self-regarding feelings to a degree that finds utterance in self-reproaches and self-revilings, and culminates in a delusional expectation of punishment.’

18 In Alan Moore’s novel *Jerusalem*, a gang of archangels plays billiards for human souls in a dingy snooker hall in Northampton.

19 The ‘I’ in *Melencolia I* may indicate that the image was intended to be the first of a series. If so, the others were never created or have not survived. One possibility is that it refers to imagination as the first and lowest of the three categories of genius, the next being reason, and the highest the spirit. Another is that the ‘*I*’ is for *Ite* – Latin for ‘go’, in which case the title would mean something like ‘Go away, Melancholy’.

20 Leonardo’s outline for a treatise entitled ‘On the Nature, Weight and Movement of

Water', for example, proposes fifteen separate books. It contains dozens of notes on phenomena each demanding meticulous observation but ultimately goes nowhere, because Leonardo does not pursue the issues systematically.

21 Modern physics says that fundamental particles can be divided into two groups: particles of spin ½, which make up the matter of the universe, and particles of spin 0, 1 and 2, which give rise to the forces between matter. Two particles from the former group can never be in the same place at once but an indefinite number from the latter group can. Fundamental particles are emergent phenomena of quantum fields, which in turn are thought to arise, together with space-time, from covariant quantum fields.

22 Albert Einstein was not an especially gifted mathematician but, like Galileo, he recognized the power of maths to explain the world. Still the puzzle remained as to why. 'The eternally incomprehensible thing about the world,' he wrote, 'is its comprehensibility.' The physicist James Hartle has a simple answer: 'The world must be comprehensible in order for information-gathering and -utilizing systems, including human beings like us, to exist [in the first place].'

23 'No question is more sublime than why there is a Universe.' Derek Parfit

24 Working with two professional astronomers, Dürer made the first printed star map in 1515. It depicted the sky of the southern hemisphere, and left large areas blank ... for future exploration.

25 Hume argued, principally, that the laws of nature are invariant, and human testimony is unreliable.

26 Cardano was a brilliant polymath but often short of money, and his disputes over gambling debts are said to sometimes have ended in knife fights. His *Liber de ludo aleae (Book on Games of Chance)* of 1564 is the first systematic treatment of probability in European mathematics. He is said to have predicted the date of his own death and made sure he won by killing himself when the day arrived.

27 Writing in the early 1980s, Thomas gave the seven wonders, leaving the greatest until last, as:

(1) bacteria that thrive on deep-ocean hydrothermal vents;
(2) oncideres, a beetle that lives in mimosa trees;
(3) the scrapie virus;
(4) olfactory receptor cells;
(5) termites;
(6) any human child;
(7) the world, seen as a living system.

28 Ludwig Wittgenstein's observation – 'How small a thought it takes to fill a whole life' – is text enough for 'Proverb', a remarkable musical composition by Steve Reich.

29 'Two things fill the mind with ever new and increasing admiration and awe ... the starry sky above me and the moral law within. The former view of a countless multitude of [stars] annihilates ... my importance as an animal creature, which after ... a short time must again give back the matter of which it was formed to

the planet it inhabits (a mere speck in the universe). The second, on the contrary, infinitely elevates my worth as an intelligence ... reaching into the infinite.' Immanuel Kant

30 Consider what the historian Sven Beckert calls 'war capitalism': 'If our allegedly new global age is truly a revolutionary departure from the past, the departure is not in the degree of global connection but the fact that capitalists are for the first time able to emancipate themselves from particular nation states.'

31 'We will always be at the beginning of infinity, alike in our infinite ignorance.' David Deutsch

32 In her memoir of the writing life, Annie Dillard also quotes Thoreau: 'The youth gets together his materials to build a bridge to the Moon, or perchance a temple or palace on Earth, and at length the middle-aged man concludes to build a woodshed with them.'

1

THE RAINBOW AND THE STAR

Light

The changing of bodies into light, and light into bodies, is very conformable to the course of nature, which seems delighted with transmutations.

Isaac Newton

'Yes, I have a pair of eyes,' replied Sam, 'and that's just it. If they wos a pair o' patent double million magnifyin' gas microscopes of hextra power, p'raps I might be able to see through a flight o'stairs and a deal door; but bein' only eyes, you see, my wision's limited.'

Charles Dickens

On a February morning in 1962, US Marine Colonel John Glenn squeezed into a capsule on top of a rocket and was hurled more than a hundred miles up into space. He orbited the Earth three times in just under five hours before gravity's rainbow plunged him safely into the Atlantic Ocean.

In those five hours Glenn flew through three days and three nights. His first day, lasting some forty-five minutes from launch at Cape Canaveral, took him over the Canary Islands and Kano in Nigeria before he saw the Sun set over the Indian Ocean on the other side of Africa. Twilight, he said, was beautiful. The sky in space was very black with a thin band of blue along the horizon. The Sun set fast, though not as fast as he had expected. Brilliant orange and blue layers spread out on either side of it, tapering towards the horizon. It was night by the time he flew over the Australian coast near Perth. Over the Pacific he was preparing for his first dawn.

As the Sun rose over Kanton, an atoll in the Phoenix Islands about halfway between Fiji and Hawaii, Glenn reported seeing thousands of tiny glowing orbs outside the capsule. 'They're brilliantly lit up like they're luminescent. I never saw anything like it ... they're coming by the capsule and they look like little stars. A whole shower of them coming by. They swirl around the capsule and go in front of the window and they're all brilliantly lighted.' For Glenn, the sight of these orbs, which disappeared as his craft moved into sunlight, was one of the most moving experiences of his flight. He was a deeply religious man, and their angelic appearance stayed with him for a long time afterwards.

NASA later determined that the orbs were Glenn's urine, frozen into perfect spherical droplets as it vented from the spacecraft. It's easy to laugh at the bathos, or deflation, in this discovery. The whole enterprise of the US space programme in its first years – employing hundreds of thousands of people and soaking up a sizeable portion of the federal budget – was, after all, in large part a giant pissing contest with the Soviets. But wonder and humour are not mutually exclusive, and the orbs were evidently a marvellous sight, however lowly their origin. They even have a kind purity compared to the haze of manmade junk that now orbits the Earth, and the wonders of Glenn's flight, arcing briefly above the Earth at 28,000 kilometres per hour (or 7,843 metres per second), are no less great for it.

Speed

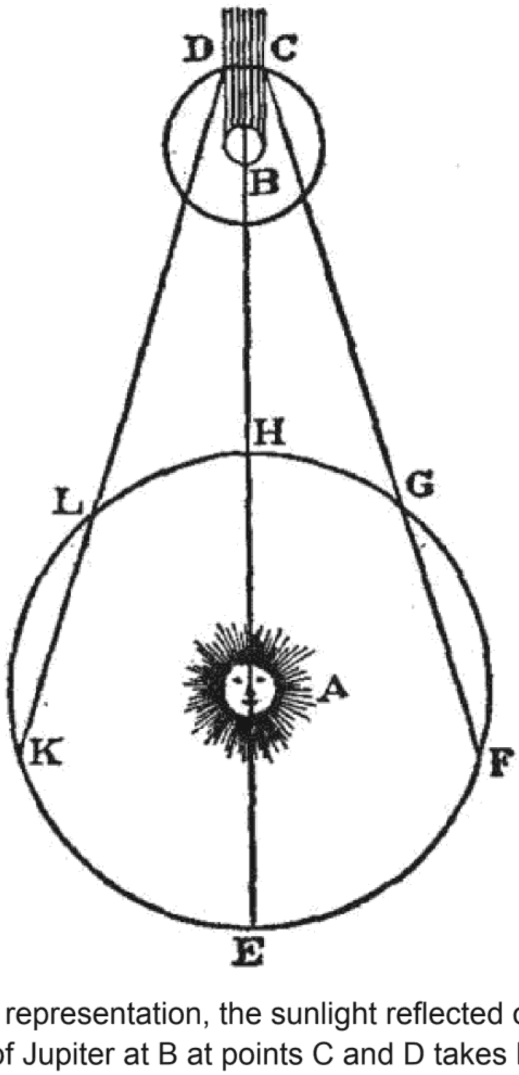
Whether in low Earth orbit or in dappled shadows on a wall, many phenomena associated with light arouse profound wonder. Discussions of its nature are often freighted with mystical and religious associations, not least in Western culture – see, for example, the opening of Genesis. But I will start with a brute fact – which is also a mystery – the speed of light.

Unlike a gust of wind or the swiftest arrow, light appears to already be everywhere that it is – to travel everywhere in no time at all. Common sense might suggest that its speed is therefore infinite.[1] From ancient times, a few thinkers challenged this view, but only from the seventeenth century onwards are there records of attempts to actually prove otherwise. Galileo Galilei suggested placing a lantern on a distant hillside at night, uncovering it at a given moment and attempting to measure the time before this uncovering was observed some distance away. This only showed that light must be extraordinarily quick. A way to measure the speed of light was found, however, by using observations undertaken for an entirely different purpose.

In 1610 Galileo pointed a telescope at Jupiter and found four bright moons, hanging like ship's lanterns[2] on a calm night at sea, orbiting it. It was a momentous discovery: compelling evidence that not all heavenly bodies go around the Earth, and a challenge to the teachings of the Church. But Galileo also thought he saw a practical application. The regular motion of Jupiter's moons could, he suggested, be used as a kind of clock in the sky. Navigators and mapmakers anywhere in the world should be able to observe when the moons appeared or disappeared behind the planet and compare the local solar time of these eclipses to standard time at a place of known longitude. From the time difference they should be able calculate their relative longitude.

The idea made perfect sense. Footage captured as the *Juno* space probe approached Jupiter in 2016 does indeed show its moons orbiting the planet like the hands of a heavenly clock. But turning the idea into a reality proved to be beyond the reach of seventeenth-century measurement techniques. In the attempt, however, Ole Rømer, an astronomer working at the Paris observatory a generation after Galileo, compiled extensive data on the motion of Io, Jupiter's innermost moon, and found a strange anomaly. When the Earth was nearest to Jupiter, the eclipses of Io (which goes around it once every forty-two-and-a-half hours) occurred about eleven minutes earlier than predicted. Six months later, when the Earth was farthest from Jupiter, the eclipses occurred about eleven minutes later than predicted. Rømer knew that the amount of time it took Io to travel around Jupiter could have nothing to do with the relative positions of the Earth and Jupiter, and realized that the time difference must be because light travelled at a finite speed: light was taking about twenty-two minutes longer to reach the Earth from Jupiter when the two planets were on opposite sides of the Sun than when they were on the same side. Determining the speed of light was simply a matter of dividing the diameter of the Earth's orbit by this time difference.

Rømer did just that, and in 1676 he calculated the speed of light to be about 210,000 kilometres per second. We now know that he underestimated its true value (which is nearly 300,000 kilometres per second) because he mistook the maximum time delay between eclipses of Io and the diameter of the Earth's orbit around the Sun. But it was a stunning result: powerful evidence that not only is the speed of light finite (though astonishingly fast) but that it can be measured by experiment.



In Rømer's schematic representation, the sunlight reflected off Io as it passes into and out of the shade of Jupiter at B at points C and D takes less time to reach the Earth when the Earth is at G or L on its orbit around the Sun at A than it does when the Earth is at F or K..

Even now the speed of light remains hard to conceive. In a 1982 essay, Annie Dillard describes witnessing a solar eclipse. In the second before the Sun goes out, a wall of shadow races towards the hill on which she and her companions stand. It roars up the valley, slams their hill and knocks them out:

'the monstrous swift shadow of the Moon.' Dillard learns later that the Moon's shadow was moving at 1,800 miles an hour (or about 2,900 kilometres per hour), and says that language can give no sense of this sort of speed. And yet this terrific rate – nearly two and half times the speed of sound in air – is in the region of a million times slower than the speed of light.

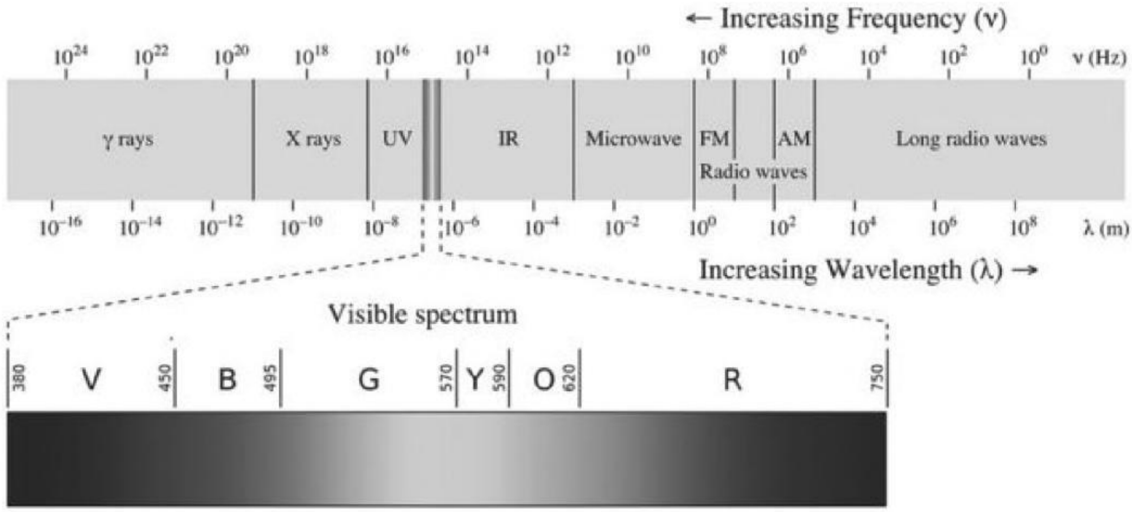
Consider an athlete on the blocks at the start of a hundred-metre sprint. He or she may take almost a seventh of a second to react to the starting gun. By that time, the 'b' of the bang will already be about halfway to the finishing line. The light from the flash of the gun, meanwhile, will already have travelled about 100,000 kilometres – the equivalent to two and a half times around the world. If, like another kind of strange particle we will come to later, the particles of light that we call photons could pass straight through the Earth and out the other side without slowing down, they would take about four-hundredths of a second to do so – barely enough time for a hummingbird to flap its wings twice.

What is light?

For what it is worth, the nature of light can be described in a few words. The problem is that many of those words and the concepts behind them are remote from everyday experience and stretch the powers of comprehension of those of us who are not specialists. One can say, for example, that visible light is a tiny part of the electromagnetic spectrum, and as such a self-propagating transverse oscillating wave of electric and magnetic fields able to travel through a complete vacuum. One can also say that light is made of particles called photons,[3] which are the smallest quantity of energy that can be transported, and that it is the force carrier for electromagnetism which (along with gravity and the strong and weak forces)[4] is one of four known fundamental forces in the universe.

If little of that is especially helpful, the following may not be either. Photons (the particles of light) have no mass and no charge, but they are exchanged between charged particles such as electrons and protons whenever they interact. They cannot come to rest, but only transform; and, for reasons that are not yet fully understood, they travel at the speed limit for all that is.

When you first hear that light is made of particles, it seems reasonable to ask how big they are. But there is no good answer to this question, because the 'particle' label is a half truth. In physics, common-sense notions based on our perceptions of the world don't always apply. Actually, many things that are easily visible to the naked eye don't obey common sense either. The fact that the Moon is a solid rock weighing more than 73 billion billion tonnes but shows no sign of falling out of the sky is one example. The persistence of separate taps for hot and cold water in public washrooms in Britain is another. And unlike anything we can easily conceive, photons sometimes behave like particles and sometimes like waves.



Visible light as a proportion of the electromagnetic spectrum.

If pressed, however, some physicists (maybe just because they want you to go away) will tell you that one way to think about the size of a photon is to consider its wavelength. But how big is *that*? The answer is that for visible light it ranges from about 400 nanometres for violet light to 700 nanometres for red. A nanometre (abbreviated nm), is a billionth of a metre, and this too is hard to comprehend. But try the following. Imagine the last joint of your little finger expanded to the size of a typical room in a house. Each of the billion or so cells in it would be about the size of a grain of rice. Green light in the middle of the visible spectrum (at around 550nm) would have a wavelength about a twentieth of the length of each grain.

But the wavelengths of the electromagnetic spectrum extend over a much larger range than visible light, so photons can be a lot smaller or bigger than this. Those of gamma rays are measured in picometres – trillionths of a metre. This makes them around a thousand times smaller than an atom. (To envisage the size of an atom, consider that a grain of salt contains about a billion billion, or 10^{18}, of them – about 10 million times the number of stars in the Milky Way galaxy.) By contrast, microwaves used to heat food approach the dimensions of a grapefruit (note to self: do not microwave grapefruit), and radio waves can be anything from a few metres to many kilometres long.

Light and sight

The existence of light is a profound wonder. So too is the fact that we can see it. Photons in the range of visible light are the only elementary particles that our ancestors evolved to be able to detect directly. The reason we see light in the wavelengths we do – the wavelengths that create all the colours and shades in our world – has a lot to do with the fact that most of the sunlight that reaches the surface of the Earth (and also travels through water) is in these frequencies. If we could see electromagnetic waves from other parts of the spectrum, the world would look completely different. Gamma rays alone would show the Moon as brighter than the Sun. Seen with X-rays, everyone's birthday suit would be transparent and we would all be dancing around in our bones, like the Mexican Day of the Dead.

The science of how we see is incredibly complicated and only partly understood. The human brain, which is probably the most complex single thing in the known universe, allocates a significant proportion of its circuits to processing the light that enters our eyes. But some of the basics of how the eye works can be outlined in a few short paragraphs.

Light passing through the pupil and lens is projected onto the retina, which is lined with light-sensitive cells called rods and cones. The cells are packed next to each other like pencils in a box, with their ends (flattish in the case of the rods, somewhat pointed in the case of the cones) facing the light. Each retina has about 120 million rods and 6 million to 7 million cones. Rods, which are sensitive to light intensity, are mostly distributed around the outer regions of the retina, while cones, which are sensitive to colour, are mostly concentrated in the middle.

Rhodopsin

Each rod contains about a billion molecules of rhodopsin, a protein sensitive to light, which are stacked on transparent plates facing towards the light. A single photon strike is enough to tweak the shape of a central part of these amazing molecules, which are called chromophores, and this gives rise to a cascade of effects via intermediary molecules which amplify the original signal hundreds and thousands of times. Until recently it was thought that it took a minimum of about seven simultaneous photon strikes to create a signal strong enough for the rod to tell the brain that light is present, but experiments have now shown that some people can detect a single photon. Test subjects have described the sensation as ‘almost a feeling, at the threshold of imagination’. At any rate, our eyes can be exquisitely sensitive and, once they have adjusted, enable us make our way by nothing more than starlight. Yet our visual system is also robust enough to allow us to discriminate objects clearly in daylight more than 10 billion times as bright. Dappled sunlight reflected on a wall lies somewhere in the mid-range of our vision.

At the centre of the retina and comprising about one per cent of its total area is the fovea: a cup-shaped depression about the width of a poppy seed. The fovea is lined with cone cells, which are thinner than the rods – just one-millionth of a metre across compared with about five-millionths – and more densely packed. This allows them, together, to achieve far greater spatial resolution. Indeed, about half of the information reaching the brain from the eye comes from here. It is the fovea that, in good light, allows you to focus on the fine details of a spot directly in front of you. Even in healthy young eyes that spot is just two degrees across, or about the width of your thumbnail at arm's length. It's up to your brain to put together an impression[5] of a whole scene from a torrent of narrow snapshots taken largely with the fovea many times a second.

The physician Thomas Young laid the foundations for our modern understanding of colour vision in 1802, when he noticed that all colour sensations could be produced by combinations of red, green and blue, and proposed[6] that there are three types of nerve in the eye, each one sensitive to one of these colours. In the twentieth century the nerves were identified as the cone cells in the retina and they did indeed come in three varieties, with each kind containing one of three different kinds of opsins (light-sensitive proteins) that absorb light at different frequencies. The first variety absorbs more light towards the longer end of the visible spectrum, which we see as red, while the second peaks in the middle of the spectrum, which we see as green, and the third towards the shorter end, which we see as blueish. Fifty years later, the physicists Hermann von Helmholtz and James Clerk Maxwell refined Young's work, and Maxwell applied what we now call the trichromatic theory to create the first colour photograph. Almost every colour image you see today is based on a distant descendant of his technique.

The artist Ben Conrad wearing his pinhole suit and helmet with 135 pinhole cameras (1994). Unlike a pinhole camera, which captures a wide area in equal focus, our eyes hold only a 'pinhole' area – a tiny sparkling fragment of reality – in focus at any one moment.

Cones need a lot more light than rods to fire, which is why we don't see much colour in low light. And the colours we do perceive depend on how many of each type of cone are stimulated and how strongly at a given moment, with the eye and the brain averaging the signals from many cones. So, for example, yellow is perceived when cones sensitive to the reddish part of the spectrum are stimulated slightly more than those sensitive to the blueish part. You may have noticed that you are able to distinguish more shades of green than any other colour, and that those greens tend to remain visible for longer as the light fades. This is because human eyes are especially sensitive to green light, which, with a wavelength of around 555nm, stimulates two of the three kinds of cones: the ones sensitive to longer-and medium-frequency visible light.

It is hard to say why certain combinations of wavelengths produce particular colour sensations. The philosopher Alva Noë points to the case of yellow. You can get yellow by mixing red and green light, he observes, just as you get purple by mixing red and blue. But yellow isn't reddish-green or greenish-red in the way that purple is reddish-blue. In fact, Noe says, there is no such thing as reddish-green. Moreover, 'you don't see red or green in yellow the way you see blue and red in purple. Yellow, like blue and red, but not like purple, is unary, not binary.' The psychologist and neuroscientist Michael Graziano suggests our sensation of white is a puzzle. White, he says, should be 'the dirtiest, muddiest colour possible' because it contains a mixture of all wavelengths in the visible spectrum. But the brain's model of white light is a high value of brightness and a low value of colour: a purity of luminance – and a physical impossibility.

'Rays [of light themselves] are not coloured,' wrote Isaac Newton in 1704, '[and] in them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour.' Three hundred years later this is still largely the accepted wisdom: colour is described as a part of how the brain interprets information rather than as a representation of some absolute, objective reality. It can tell us about motion, for instance: a black-and-white wheel set spinning can reveal the rainbow. And it can tell us about depth: distant hills typically appear blue in bright daylight because – just as happens when we look at the sky above our heads – the volume of air between us and them scatters blue[7] light more than it does the longer wavelengths. According to the philosopher Mazviita Chirimuuta, 'colours are not properties of minds, objects or lights, but of perceptual processes – interactions that involve all three terms'. In what she calls 'colour adverbialism', colours are not properties of things but ways that stimuli appear to certain kinds of individuals or even cultures. 'Instead of treating colour words as adjectives, we should treat them as adverbs. I eat hurriedly, walk gracelessly, and on a fine day I see the sky bluely!'

If human colour vision sounds like a bit of a kludge that's because it is. But it's a pretty good kludge. Depending on whom you talk to, we can distinguish anything from tens of thousands to millions of different colours. In reality, our eyes distinguish only about a hundred and fifty hues, but our visual system takes account of at least two other factors to create the experience we call 'colour'. First, there is brightness – the amount of light emitted or reflected by an object. Second, there is saturation – the intensity of a hue, where a less saturated colour is duller and a highly saturated one is more vivid. Combining hue, brightness and saturation in varying degrees produces the enormous range we experience. There are other factors at work too: context also influences colour perception. In the checker shadow illusion, for instance, squares that are actually the same colour appear to be totally different because the brain interprets one of them as being in shadow.

How does our colour vision compare to that of other animals? While it is inferior in some respects to that of birds and bees, which can see ultraviolet, it turns out that it is actually superior to that of the mantis shrimp, which became famous, as obscure and weird crustaceans go, for having twelve or more different kinds of colour-sensitive opsins in the cone cells of its eyes compared to the three in ours. In the deep and distant past, also known as 2013, researchers assumed that such a range of opsins would give these animals superbly refined colour discrimination. It turns out that the opposite is true: mantis shrimps are actually terrible at telling colours apart. Thanks to other adaptations, however, they can see linear, circular and elliptically polarized light – capabilities that must reveal to them things we can only begin to imagine in the movement of water and light reflected from the bodies of their prey.

Weaving and unweaving the rainbow

It can be pleasant (and not entirely misleading) to visualize sunshine as raindrops[8] falling to Earth – only, of course, raindrops that are incredibly tiny, incredibly fast and incredibly numerous. Every second, about 10^{45} solar photons strike the Earth – a hundred thousand trillion for each square centimetre in bright sunlight.

Dappled light on a kitchen wall has been enough to arouse a sense of wonder in me. And it hasn't taken much more than this to inspire popular and enduring works of art. The painter Edward Hopper, for example, said his favourite thing to paint was sunlight on the side of a building. But for most of us, most of the time, wonder is more usually associated with something a little more dramatic or unusual. One such phenomenon arises when a shower of photons and a shower of water interact to make a rainbow.

Virtually every culture has stories associated with rainbows. Many Aboriginal Australians revere the Rainbow Serpent, an enormous beast that lives in the deepest waterholes. Descended from an even larger being visible at night as a dark streak in the Milky Way, the Rainbow Serpent reveals itself as it moves through water and rain. It shapes landscapes and sings places into being, and it can be malign or benign. Sometimes it swallows and drowns people, or blights them with weakness, illness and death. At other times it endows them with rainmaking and healing powers.

In Aboriginal belief, every person has a home place in the land from which his or her spirit emerges at the beginning of their life. As one elder puts it: 'We all come from the Rainbow.' And at the end of life, every human spirit must be ritually returned to its home in the dark, invisible underworld. In this cosmology the rainbow is not an arc but a circle, half hidden within the land, connecting the life force in earth and sky. The movement of water through the material world enables the reproduction of organic beings, as well as the spiritual movement of persons from the dark recesses of the invisible world inside the land out into the light and animation of material being and back again – an example of what the geographer Yi-fu Tuan calls a 'hydro-theological cycle'.

Other cultures have diverse stories about the rainbow. In ancient China it was a slit in the sky sealed by the goddess Nüwa using stones of five different colours. In Greenland it was the hem of a god's garment. In Wales it was the chair of a goddess, and in Armenia the belt of the sun-god. The Blackfoot Indians of North America called the rainbow the Rain's Hat or the Old Man's Fishing Line. A Germanic myth describes it as the bowl used at the time of the creation for paint to tint the birds. The root of a Hungarian word for rainbow, *szivárvány*, derives from a verb meaning 'to draw water', and in Hungarian lore the two ends of the rainbow suck water from the world's oceans.

In the Classical Mediterranean world, the rainbow was associated with the relationship between the divine and the earthly realms. The Greeks and Romans said that it was a path made by Iris, a messenger between Heaven and Earth. (Iris is the daughter of Thaumas, a sea-god whose name is linked to the Greek word for wonder, and from which in English we have 'thaumaturgy', or the capability of a magician or saint to work magic or miracles.) Norse myth also describes the rainbow as a bridge that connects Asgard and Midgard, the homes of the gods and men. And across much of Europe and western and southern Asia there is, of course, an association with a bow. For Finns and Lapps, the rainbow was the bow of the thunder god, a skilful archer whose arrow is lightning. In Hindi it is *Indradhanush*, the bow of Indra. In Arabic it is *Qaus Quzaħ*, the war bow of Quzaħ, a pre-Islamic god.

Some cultures have regarded the rainbow as malign. The people of Nias, an island in the Indonesian archipelago notable for its megaliths, feared it as a huge net spread by a powerful spirit to catch their souls. And among many indigenous peoples of the Amazon, rainbows were associated with harm. So great was ancient Peruvians' fear of it that they believed it best to stand still in silence until it disappeared.

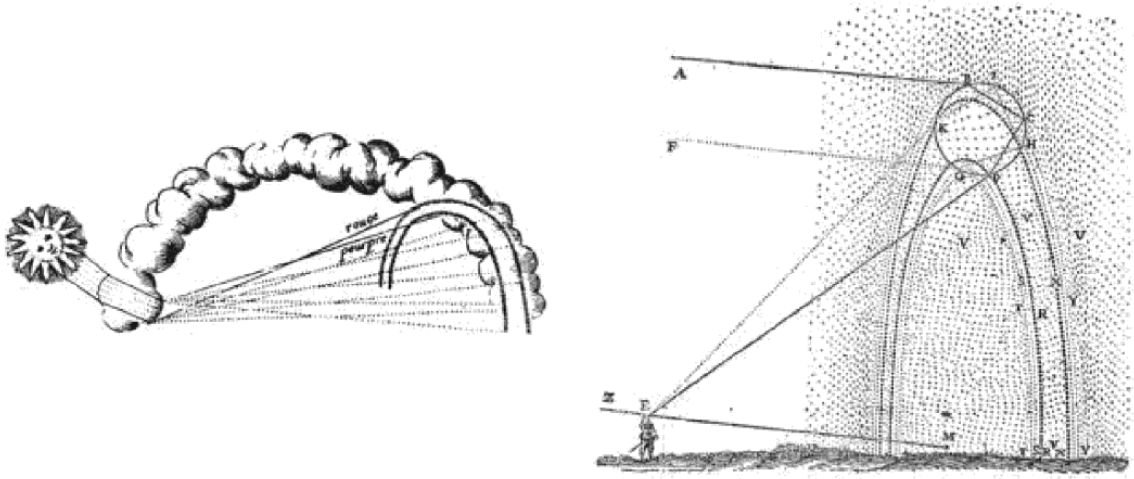
But in the modern Western imagination – influenced by the biblical account,[9] in which the rainbow is a covenant from God – its associations are overwhelmingly positive. Political and social movements have adopted it as a symbol of hope and solidarity for hundreds of years. A rainbow featured on a flag in a peasants' revolt in Germany in the sixteenth century (one of the largest and most widespread uprisings in Europe before the French Revolution, it ended with the peasants' defeat and mass slaughter). In the twentieth century a rainbow flag was flown by the cooperative and peace movements in Europe. It was also adopted by Birobidzhan, the Jewish autonomous homeland in Siberia, and by the indigenous peoples' movement in the Andes. Since the late 1970s a version has been associated with LGBT pride.

We'll never know who first suggested that a rainbow is an inanimate phenomenon without inherent significance. But the earliest surviving record of what we would now call a scientific explanation dates from the fourth century BC. In the *Meteorologica*, a treatise on earthquakes and weather phenomena, Aristotle describes a rainbow as a reflection or an echo. Light, he wrote, travels in straight lines, and is reflected back off a raincloud in a circle of angles to create the impression of a bow in the eye. The different colours – for Aristotle just three: red, green and violet – are made by light deflecting at slightly different angles.

Aristotle's explanation is partly right, but it is incomplete. Sunlight is reflected in a rainbow in a way broadly analogous to the reflection of sound, but it is also refracted – first when it enters a drop of rainwater, and a second time as it leaves the drop after reflecting off the back of it. Although Aristotle knew that light refracted through a prism or water droplet separates into different colours, he did not apply this to the rainbow and insisted that light was being reflected by an entire cloud. His account does not seem to have been seriously challenged in Europe or the Islamic world for about sixteen hundred years. Only in China (in the *Dream Pool Essays* published in ad 1088 by the statesman and polymath Shen Kuo) is there a record of the idea that rainbows are formed by sunlight refracting through individual drops of rain. New ideas start to appear in Western accounts about two hundred years after Shen Kuo. In 1266 the English monk Roger Bacon wrote that a primary rainbow never appears higher than forty-two degrees above the horizon. Then, around 1300, the Persian scholar Kamāl al-Dīn al-Fārisī and Theodoric of Freiburg independently undertook research that still forms the basis of our modern understanding. Working without any knowledge of each other, they both showed that a rainbow could be made by an ensemble of individual drops and not, as Aristotle had proposed, by a cloud or mist acting like a mirror.

Both men based their conclusions on experiment and measurement. Al-Fārisī put a spherical glass vessel filled with water – his large-scale model of a raindrop[10] – in a camera obscura, projected light into it and deduced that the colours are made by the decomposition of white light. Theodoric used glass spheres but looked closely at natural phenomena. ‘In spider’s webs,’ he wrote, ‘which are stretched out and closely covered with many drops of dew in a suitable position with respect to the sun and the eye, the colour ... yellow ... appears most plainly between the other colours ... as in the rainbow.’ And then he got right down on the ground and saw the same thing in dew drops on blades of grass – moving his head slightly, his angle of vision changed and each colour of the rainbow appeared in order. Both al-Fārisī and Theodoric also worked out that a secondary rainbow, which sometimes arcs more faintly around and over the main one, is caused by rays of light reflecting one more time within the drops, reversing the order of colours.

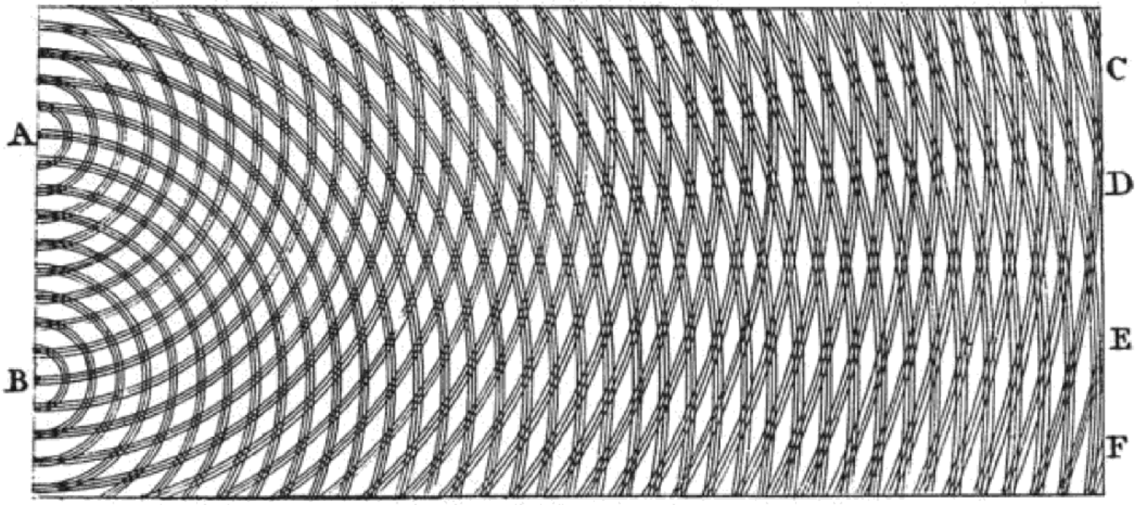
Little further progress was made until the 1620s, when René Descartes used the law of refraction[11] to calculate that a rainbow appears at an angle of 41°30' above the viewer. A generation later, Isaac Newton refined these computations. He found that a primary rainbow always occurs between 40°17' and 42°2', and a secondary one between 50°57' and 54°7'. Newton also showed that, in the right conditions, a third rainbow is created behind the viewer in a circle around the Sun. Because sunlight is so bright, however, this will always be invisible to the naked eye.



Marin Cureau de la Chambre, a contemporary of Descartes, believed sunlight was refracted and projected to make a rainbow (left). Descartes showed that the light bounced off the back of raindrops and then refracted at an angle towards the viewer (right).

By the nineteenth century rainbows seemed to hold few secrets. An experiment by Thomas Young in 1803 showed that light behaves like a wave, and the way in which these waves can interfere with each other (increasing their joint amplitude when they are in sync, and dampening each other when they are not) explained the additional bands that sometimes form on the inner arc of the primary rainbow. With the growing understanding of the dispersion and polarization of light that followed, a comprehensive explanation of the rainbow appeared to be in sight. But had it been explained away?

After a birdbath of heavenly paint, a sky pathway and a covenant with the Almighty, the rainbow as a trick of the light may seem like a letdown. Does science undo the wonder of the rainbow? Some of Thomas Young's contemporaries certainly thought so. Johann Wolfgang von Goethe attempted a new theory that took more account of human feelings, exploring how we perceive colour in a wide array of conditions, rather than seeking to develop a mathematical model of its behaviour as Newton had. William Blake decried the 'single vision'[12] of natural philosophers since Newton, and John Keats famously wrote that the rainbow, once an object worthy of awe, had been reduced to part of the dull catalogue of common things. But, as the modern scholar Philip Fisher argues, Aristotle's pairing of echo and rainbow is a poetic thought as well as a scientific one. It captures an inner similarity between two things that seem remote from one another, combining them in instantaneous perception by means of language. Nor is the work of al-Fārisī and Theodoric without beauty. When I picture a thirteenth-century monk prostrate in the wet grass and moving his head slowly from side to side in order to catch the changing colours of light refracted through dewdrops,[13] I do not see an irritable reaching after fact or an inability to live with uncertainty, but a delightful, childlike fascination and a willingness to explore the world on its own terms. A scientific approach does not have to be antithetical to a spiritual vision. Descartes' treatise on the rainbow was intended as part of a preamble to his massively ambitious *Discourse on Method* of 1637, in which he strove to determine beyond doubt what could really be known through mathematics, logic and deduction. This, he believed, was a sure route to God, the ground of all being. In that sense it was a profoundly religious project, not a mere exercise in calculation (although he did see a pragmatic and political application of his knowledge and suggested harnessing the rainbow effect in displays such as artificial fountains for the amusement of kings).

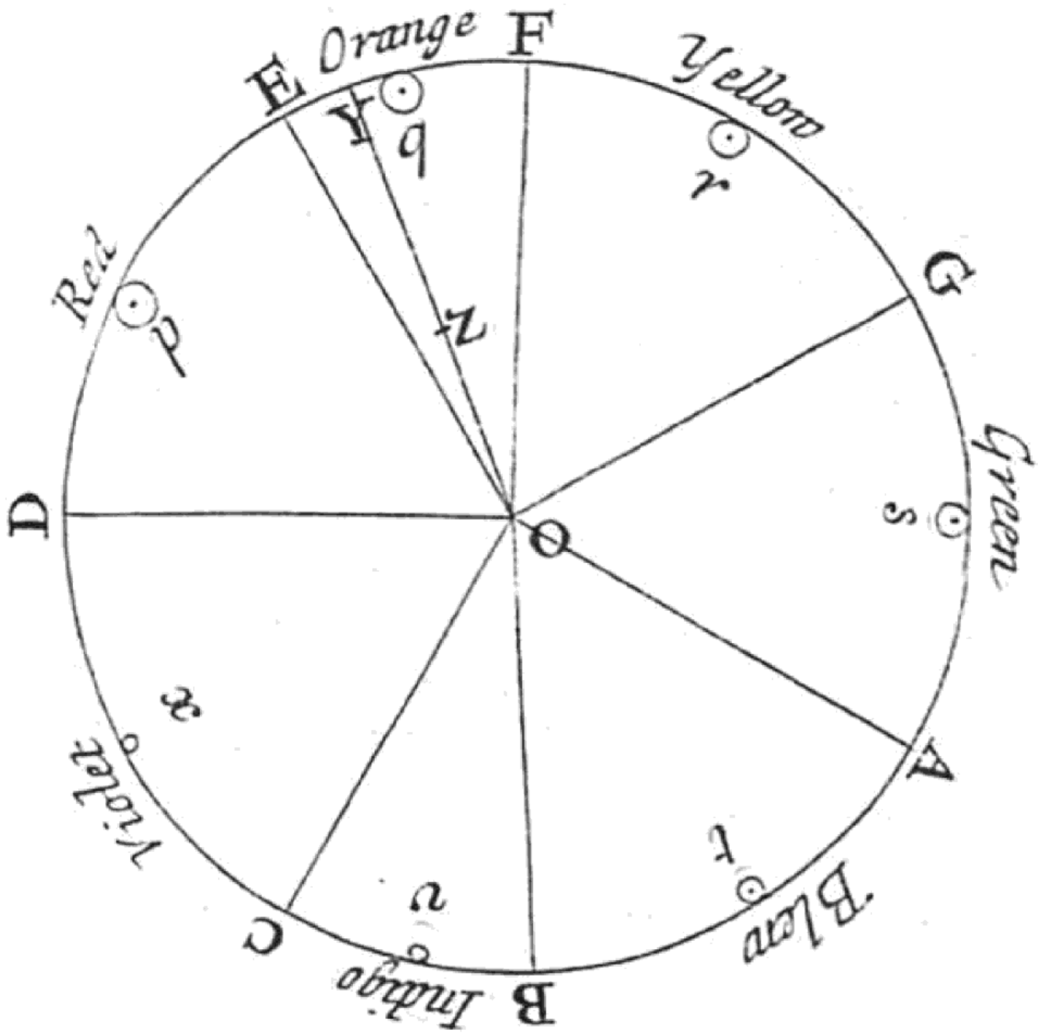


In 1803 Thomas Young used a wave tank and a double-slit interferometer to show that light behaves like a wave. Some physicists see this as the single most important discovery in the study of light.

Newton was extraordinarily fastidious in his researches into natural philosophy, or what today we would call science, and although he made some of the biggest strides taken by a single human being into our understanding of the laws of nature, he never lost sight of how limited that understanding was. He did argue forcefully that light is made of particles, but he also understood the strength of arguments to the contrary made by his contemporary Christiaan Huygens, and corroborated by Thomas Young a hundred years later, that light was made of waves, and he knew when to stop speculating.[14] 'To determine more absolutely what Light is,' he wrote, 'and by what modes or actions it produceth in our minds the Phantasms of Colours, is not so easie. And I shall not mingle conjectures with certainties.'

And yet Newton was also obsessed with biblical prophecy, devoting inordinate amounts of time to tracts with chapter titles such as 'Of the power of the eleventh horn of Daniel's fourth beast, to change times and laws'. He was a practising alchemist too, believing matter to be active and charged with spirit. This side of his character was unknown until John Maynard Keynes discovered his private papers in the early twentieth century, and concluded that 'Newton was not the first of the age of reason. He was the last of the magicians.' And at least one trace of magical thinking seeps into his work on light. Newton divided the colours of the rainbow into seven, a mystical number that he linked to the seven notes of the Western musical scale (and hence to the ancient Pythagorean notion that the world expresses a divine proportion), as well as to the seven classical planets. Today we happily recite these colour names – red, orange, yellow, green, blue, indigo and violet – even though an unprejudiced eye seldom sees them all with this degree of differentiation.

In my experience, such physics as I do understand only adds to my wonder at the all that is. And whatever is on my mind, the great dance of light, in which it passes effortlessly through itself in different directions while travelling through air or water, is occasion for meditation. For in the midst out of this 'tremendous mess', as Richard Feynman vividly described it, we sometimes find clarity. I live near a river, and kayak on it when I can. This being England, the weather is always changing. When it's sunny, and golden light flashes on the water, I find solace[15] in gliding across its surface. Typically I see a rainbow a few times a year – infrequently enough that I always look forward to another and delight like a child in something so beautiful that is simultaneously near and beyond reach. I also enjoy knowing that I am seeing something as close as I ever will to the spectral colours of what Newton called light's 'differently refrangible rays', and not the electronic composites of artificial images with which we are bombarded for so much of our lives. In a rainbow, rain really is (among other colours) purple,[16] just as Prince said.



Making an analogy to different tones in music, Newton speculated that rays of light of different magnitude, strength or vigour excited 'vibrations of various bignesses' in the aether, the medium through which light supposedly travelled, and in the retina of the eye. The biggest vibrations, he suggested, corresponded with the 'strongest' colours, reds and yellows; the least with the weakest, blues and violets; the middle with green; and a confusion of all with white. Following this analogy, it made sense to Newton that there should be seven colours like the seven tones of the diatonic musical scale. This beautiful idea was quite wrong.

A rainbow is not a sign from the supernatural. But neither is it an object that exists independently of an observer. It is like the horizon: an artefact of vision, albeit one that is also a revelation of – or at least a clue towards – what is going on in the world beyond us. Arising from the interplay of sunlight with falling drops[17] of water, it is a seemingly constant but subtly changing pattern, and as such not a bad image of consciousness itself. 'Perception,' wrote the mathematician and astronomer Johannes Kepler, 'belongs not to optics but to the study of the wonderful.' This includes our sensations of colour, which may not really be 'there' in the world but are so precious to us as means of connecting with it.

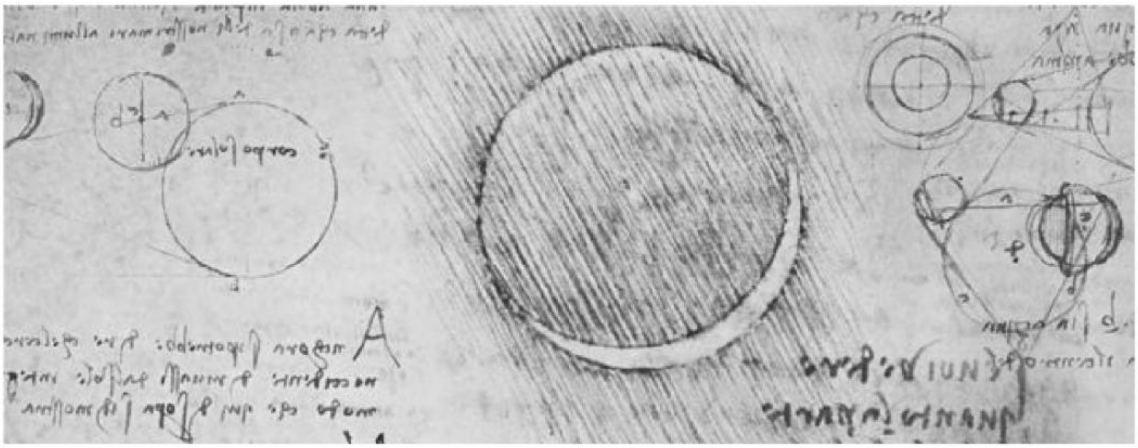
It may be impossible for humans to entirely escape allegory and metaphor in how we respond to our perceptions of natural phenomena. Recalling that the Rainbow Serpent of Aboriginal Australians is not always a benign presence, for example, and reading that an approaching storm can cause a giant repeating rainbow (the effect is caused by gravity waves in airglow, analogous to when a rock is thrown into calm water), I find myself thinking of the storms[18] of many kinds that are likely in coming years and decades.

Light beyond the rainbow

Rainbows are just one of the wonders of all the light we can see. In the optical phenomenon known as heiligenschein, for instance, a whitish glow resembling a halo surrounds the shadow cast by the viewer's head on dew-covered grass. It arises because dewdrops act like lenses, focusing parallel beams of light that pass through the drops closer together so that the leaves beneath them seem brighter. In the case of the phenomenon called a glory, a bright halo appears around the viewer's shadow when that shadow falls on mist or cloud, but it differs from heiligenschein in that it has concentric rings of colour, with blue on the inside, ranging through green, yellow and red to purple on the outside. The major source of the glory's light is reflection from the back or front of the water droplets. Refraction as the light enters and leaves them accounts for the colour. In the mountains, when the Sun is low in the sky, the shadow in the centre of a glory may be greatly magnified and sometimes distorted as it falls over a larger region of rugged ground, giving rise to a Brocken spectre – an apparition of self/not-self that has frightened and fascinated people in equal measure. Today we can include among the resonances of the spectre a sense that our actual bodies are also 'just' projections: geodesics[19] in three-dimensional space of phenomena in four-dimensional space-time.

Turning from shadows towards the source of light itself, a sundog (which is also called a phantom sun or parahelion) projects bright 'echo' Suns on either side of the real thing, frequently with a luminous ring all the way round. It is created by the refraction of sunlight through flat ice crystals that are falling slowly through the air many thousands of metres above the ground. Higher still, and quite different in origin and appearance, an aurora is a rapidly shifting curtain of colour, often mostly green, that appears when charged particles from the Sun hit and ionize atoms in the magnetic field high above the Earth. In footage from the International Space Station you can watch seemingly endless auroras scroll over the curve of the horizon like the puddles of cool flame from brandy burning on a giant Christmas pudding.

Some wonderful effects of light in space are easily visible from the ground. Earthshine[20] – light reflected from the sunlit side of the Earth onto the dark disc within the bright narrow crescent of a new or old Moon – is one of my favourites. Most clearly visible when the Moon is close to the horizon at dawn or dusk in calm and clear weather, it makes it seem especially close – a Janus on the threshold[21] between different realities. At a given moment and place on the ground or at sea, Earthshine does not vary, but its hue and intensity will change according to where you are on Earth because the reflectivity of the ocean, land or cloud around you will be different. Earthshine on the Moon is a subtle and gentle light to us, but the view from the part of the Moon that is within Earthshine would be breathtaking: a dazzling blue, green and white orb in the sky four times wider than the Sun and fifty times brighter than the full Moon as it appears on Earth.



Sketch of Earthshine by Leonardo da Vinci (1506 to 1510).

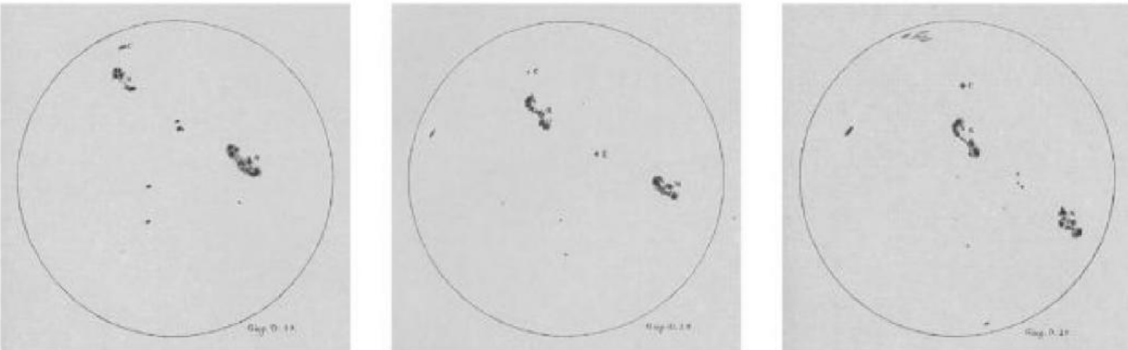
A catalogue of the wonders of light on Earth could go on for a long time. It could include the appearance of Sirius, the brightest star in the sky, which appears to pass through the entire visible rainbow of colours as its light is refracted through the atmosphere. It could include zodiacal light:[22] the diffuse glow visible in the sky after dusk and before dawn that is a reflection of sunlight from trillions of tiny dust grains – no more than one in every cubic kilometre – that did not make it into planets or asteroids of the solar system. And this before we even got started on the trickster properties of light itself. (One of my favourite examples, highlighted by Richard Feynman, is that you can take a piece of mirror, scratch away part of its surface, and the mirror will reflect light at an angle it didn't before.) But I will pass on to the shared origin of many of them: the Sun.

Staring at the Sun

For most of recorded history (and, we may presume, for long before), people have been in awe of the Sun. Often they have given it a central place in religion. But until less than a hundred years ago almost nobody had a very good idea of what it was or knew what made it shine.

To look directly into the Sun for more than a few moments can cause blindness, but thanks to recent technology we are now beginning to appreciate its true magnificence. A video by NASA's Solar Dynamics Observatory published in 2015 compresses five years of detailed observations into a few minutes. The roiling contortions, vortices and outpourings are so utterly fascinating that for a time you can only stare, forgetting almost everything else.

The NASA film is mesmerizing, but the first movie of the Sun was made in 1613. Over successive days in June and July of that year Galileo projected an image of the Sun though a telescope onto a screen and recorded the position of spots on its surface. The drawings he made rival photographs taken hundreds of years later in their quality and, viewed in sequence like frames from a film or a flick book, show the spots moving smoothly across the star.

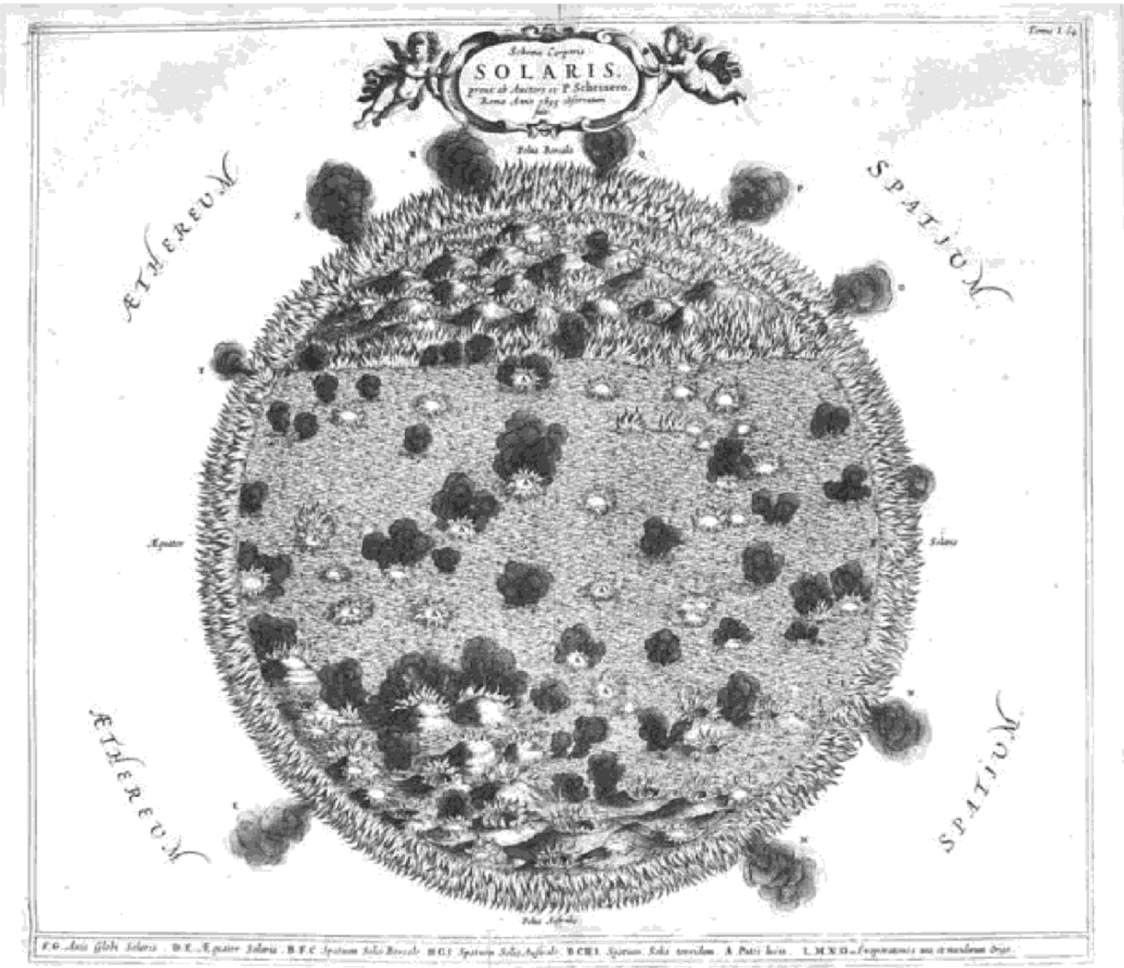


Every day from 2 June to 8 July 1613 Galileo drew the spots he was able to see on the Sun. Here are three in the sequence of thirty-five images

People had known about sunspots for a long time. The earliest surviving written record, which was made in China, dates from around 800 BC, and many cultures have stories about them. It is reported, for example, that the ancient people of the Zambezi believed sunspots were mud spattered in the face of the Sun by a jealous Moon. Galileo was not even the first person to observe them through a telescope. The mathematician Thomas Harriot had done so in 1609. But Galileo and another observer named Johannes Fabricius were the first to surmise that the movement of sunspots across the Sun and their disappearance off one edge followed by their reappearance on the other showed that the bright disc was actually a rotating sphere which carried the spots along as it turned. And it is in Galileo's drawings that we can see most clearly the first step in transforming the Sun from an object of dazzling unknowability into something knowable but no less astonishing.

For a long time after Galileo, astronomers learned very little more about the nature of the Sun. Some of the speculation was, by turns, astute and wildly wrong. Descartes thought that the spots were scum on a primordial ocean. The seventeenth-century polymath Athanasius Kircher depicted a fantastical boiling ocean with spouting lakes of fire. William Herschel, the eighteenth- and early-nineteenth-century astronomer who discovered Uranus, suggested that sunspots were portholes into a darker world where people lived beneath the radiant outer sheath. But almost no one had much by way of actual evidence, and in 1835 the philosopher Auguste Comte concluded that, short of travelling there, it would always be impossible to study the chemical composition of the Sun or other stars. But Comte was wrong. The Sun does tell us what it is made of, if only we know how to look.

In 1802 the chemist William Wollaston found that if he passed sunlight through a narrow slit in a piece of metal before it entered a prism he could see several thin black vertical lines amid the vivid colours of the solar rainbow it projected. The physicist Joseph Fraunhofer repeated the experiment in 1814 with better equipment, and proved that the apparent continuity of a rainbow is an illusion: there are tiny gaps, dim or black arcs of missing colours, too narrow for the human eye to see. Fraunhofer had invented the spectroscope, and with it he eventually catalogued more than five hundred gaps, known today as Fraunhofer lines (or absorption lines), in the spectrum of the Sun. Today, tens of thousands are known. It turns out that the Sun, our universal light, does not emit light across the entirety of the visible spectrum.



Schema Corporis Solaris, or the Sun, by Athanasius Kircher (1665).

Another revelation followed half a century later when Robert Bunsen and Gustav Kirchhoff heated various chemical elements and observed the light they gave off through a spectroscope. When mercury, for example, is vaporized, the hot gas glows blue to the naked eye. But when this light is passed through a slit and then a prism it appears as violet, green and yellow. Bunsen and Kirchhoff realized that the blue is actually the impression created when the eye blends those three colours. A spectroscope, they now understood, displays the 'true' spectral colours given off by any hot material and, experimenting with different elements, they found that each has its own unique fingerprint. Sodium, for instance, gives off a tightly spaced pair of golden lines. Turning a spectroscope at the Sun, Bunsen and Kirchhoff matched its black-line patterns against the bright-line patterns of dozens of elements, notably hydrogen, oxygen, iron and calcium. By the late 1860s they had matched all of the lines to elements known on Earth except for one series in the yellow part of the spectrum. The mysterious lines were interpreted as the signature of a completely unknown element, and named 'helium' after the Greek sun-god Helios. Many thought that helium existed only in the Sun, but in 1895 it was discovered on Earth when the chemist William Ramsay isolated a gas from deep in a uranium[23] mine and, passing it through a spectroscope, accounted for every remaining unexplained line in the yellow spectrum of the Sun. In this way the chemical composition of the Sun was finally known.

The answer to the question of what made the Sun shine came from linking the discoveries of spectroscopy to advances in theoretical physics. Albert Einstein's famous formula $E = mc^2$, published in 1905, showed that matter can be turned into energy and, grasping the significance of this, the astronomer and physicist Arthur Eddington proposed in 1920 that vast amounts of energy are released as light and heat when one of the protons (the nuclei of hydrogen atoms) within it combines with another to form helium. In the 1930s the physicist Hans Bethe and others showed that the process in stars like the Sun is rather more complicated, but this is, in broad outline, what we now call fusion.[24] It turns out that every second the Sun transforms about 4.25 million tonnes of its mass into energy and light in this way. This is the equivalent of more than 90 billion megatonnes of TNT – that's about seventy-five thousand times the yield of a B83, the most powerful hydrogen bomb in service with the US military today, or 6 trillion Hiroshima atomic bombs. That said, there are huge differences between the Sun and a nuclear device. For a start, the Sun releases its energy relatively slowly and constantly, and the fury within is tamed by hundreds of thousands of kilometres of gas between its core – where the reactions take place – and its surface.

Nearly all of the fusion in the Sun takes place in its core, which occupies about the same proportion of the whole as the stone does of a peach. Here, under enormous pressure and gravity, the temperature exceeds 15 million degrees Celsius, and atoms exist as plasma[25] – the fourth state of matter, in which atoms are too hot to be solid, liquid or gas. The surrounding sphere heats up as energy is transferred outwards through successive layers before it reaches the surface of the Sun and escapes into space. But this does not happen quickly. Hydrogen and helium are so densely packed in the core that the photons produced by fusion move tiny distances before bumping into other atoms, where they are absorbed and then emitted again. As a result, photons take a random walk for as much as two hundred thousand years before they reach the surface of the Sun about 500,000 kilometres above the core. Once in space, they can cover that same distance unimpeded in less than two seconds, and those that fly towards the Earth cross the intervening 150 million kilometres in eight minutes and twenty seconds. This means that the light from the Sun that you see began its existence in a reaction that took place as long ago as the time that anatomically modern humans evolved.

The temperature at the visible surface of the Sun, which is known as the photosphere, is less than four ten-thousandths of that in the core. But, at an average of 5,500°C, it is still more than three times the temperature of molten lava or the melting point of iron. Like some superheated bowl (or ball) of soup, however, this is a turbulent place, and conditions at the surface vary. Large bubbles of hot plasma move upwards to the photosphere in some places but in others strong magnetic fields slow or block their rise. Slow-moving matter is cooler – in this case, as low as 4,000°C – and cooler means darker. These areas of stronger magnetism on the surface are the sunspots that Galileo drew with such care.

The weather on the Sun

The idea that the Sun affects the weather on Earth is familiar. Less so is the fact that the Sun itself has incredibly vast and violent weather of its own. Above the Sun's bright visible surface, magnetic field lines flow outward and curve back towards the surface in arcs that dwarf the Earth in scale. Highly charged plasma follows these arcs and when, sometimes, the magnetic lines connect with others or disconnect, the plasma snaps together or breaks apart, like a rope breaking under tension, at great speed (and fast means hot: temperatures can rise to millions of degrees). These whips of highly charged, fast-moving plasma are the Sun's corona – so called because when seen during a total eclipse they look like the points on a crown. As the solar wind cools the corona, some matter escapes into space. But much of it falls back down to the surface. In other words, it rains on the Sun – with droplets of slightly cooler (but still very hot) plasma the size of countries falling from altitudes of over 60,000 kilometres at speeds of more than 200,000 kilometres per hour.

There are also tornadoes on the Sun. Swirling plasma creates vortices, which cause magnetic fields to twist and spiral into super-tornadoes that reach from the surface into the Sun's upper atmosphere. Even more tremendous are solar flares and coronal mass ejections. In flares, plasma heated to millions of degrees along magnetic arcs ejects electrons, ions and atoms (as well as electromagnetic radiation mostly outside the visible range) into space at near the speed of light. Coronal mass ejections squirt particles out into space at about only two per cent of the speed of light, but this is still millions of kilometres an hour, and they eject much more mass than flares. 'Limpid jets of love hot and enormous, quivering jelly of love, white-blow and delirious juice,' wrote the poet Walt Whitman in a very different context. When, some days later, the outer edges of these ejections lick the Earth's magnetosphere they cause geomagnetic storms and unusually strong auroras[26] at the Earth's poles.

All this activity is ultimately linked to processes deep within the Sun and in particular to what goes on at the boundary between its inner and outer spheres. The inner sphere of the Sun – its core and radiative zone – rotates almost as uniformly as a solid ball. But about two-thirds of the way from the centre to the surface – above a thin layer called the tachocline, and in what is known as the convective zone – movement is more turbulent. Here, plasma takes about twenty-five days to rotate about the equator but longer to do so at the poles. This differential sets up eddies and meridional flows – huge conveyor belts of magnetized material that flow towards the higher latitudes, where they sink and then return towards the equator. Normally, these currents dive down and start to head back at a latitude of about 60 degrees, but sometimes they travel all the way to the poles before doing so. When this happens the return is slower and the Sun becomes less active, with the result that there are fewer sunspots. Over a cycle of eleven Earth-years, the Sun 'breathes' or pulses – varying its output of solar wind, X-rays, ultraviolet and visible light.

The birth and death of the Sun

It is sometimes said that the Sun had a mother and father. Mum, in this simplified account, was a giant molecular cloud made of mostly hydrogen, and Dad was a shockwave from the explosion of a giant blue star – much bigger and denser than the Sun but tiny compared to the cloud. The maternal cloud contained almost all the other elements besides hydrogen, mixed in with the debris from previous generations of stars in a galaxy that had already been swirling and fizzing with supernova explosions for billions of years. There was nothing inevitable[27] or unique about the particular circumstances in which the cloud met the star, but about 4.6 billion years ago the two happened to be close enough to be drawn together by gravity and they precipitated from the cloud a new body: a dense ball of hydrogen known as the solar nebula. This proto-Sun was a ten-millionth of the size of the original cloud: comparatively, an apple seed to a football stadium. Myriad similar events are visible today in images such as those of the Pillars of Creation in the Eagle Nebula.

As for the end, well, many of us have a general idea that, one day, the Sun will become a red giant which will incinerate and swallow the Earth. No more cloud capp'd towers and gorgeous palaces for you, pal. The full story, though, is even more awesome and beautiful. It deserves, at the very least, a great musical score. I'd like to imagine something[28] beyond the final chord of 'Der Abscheid' in Gustav Mahler's *Das Lied von der Erde* (which, Benjamin Britten suggested, was imprinted on the atmosphere) and surpassing recent works by John Luther Adams such as *Become Ocean* (described by music critic Alex Ross as 'the loveliest apocalypse in musical history') not to mention his *Sky with Four Suns*. All I can offer, however, is a précis of the physics – a sketch for the programme notes.

Barring intervention by intelligent beings with stupendous powers (which seems like a stretch) or collision with another star (which is highly unlikely), the Sun's future trajectory is predictable in almost every respect. As the astronomer Martin Rees says, 'even the smallest insect is far more complex than a star'. But there can still be something magnificent in what is all but inevitable. Human events are unpredictable in their details but the fate of our planet is not, and maybe there is some truth in the old Norse idea that the future is determined in fibres that have already been selected and are being woven.

Fusion, which powers the Sun, will continue for as long as a fuel supply remains. The Sun is about three hundred and thirty thousand times the mass of the Earth and a million times its volume – a basketball compared to a pea. At present it is about 4.6 billion years old, and almost halfway through what is known as the main sequence in which it generates energy by fusing hydrogen into helium. At two octillion (two followed by 27 zeroes, or 2,000,000,000,000,000,000,000,000,000) tonnes, it has enough fuel to burn for billions of years yet. All through this time it will get hotter and brighter. In little more than a billion years from now the heat will be enough to evaporate away all the Earth's oceans, and the average temperature on our planet will reach over 370°C – more than hot enough to bake pizza. 'I think we are inexterminable, like flies or bedbugs,' the poet Robert Frost once said, but these conditions will trump the thermonuclear armageddon that he and his contemporaries feared. Macroscopic life on Earth, including human life, will have long since ceased.[29]

Even at this point, however, the Sun's life as a main sequence star will still be hardly more than half over, and for another four billion years it will remain just about the same size, and radiate white light just as it does today. Only about five billion years from now will hydrogen in the core finally be exhausted, and the Sun start to expand. To begin with the expansion will be slow, and the Sun will take about half a billion years to double in size. Then it will grow more quickly until it becomes a red giant over two hundred times larger and two thousand times brighter than it is today. By this time it will have swallowed and incinerated Mercury and Venus, but the Earth will probably have been pushed outwards by the expansion and continue its orbit unconsumed (though much too hot for life). It is possible that Saturn's moon Titan, which is so cold at present that liquid methane on its surface flows through its deep canyons, will have warmed to temperatures within the range comfortable for life as we know it, making it, conceivably, a refuge for our distant descendants, assuming they somehow escape the heat on Earth in time.

The Sun will be a red giant for about a billion years. During this time it will gradually burn away a third of its mass and then, suddenly, helium in the core will ignite violently in what is known as the helium flash and more than a third of what remains will turn into carbon in a few minutes. After that it will shrink from more than two hundred to around ten times its current size, and burn helium for about a hundred million years. When all the helium is finally exhausted the Sun will repeat the expansion it followed when its core was hydrogen, except that this time the expansion will be much faster, and the new giant will only last about twenty million years. The Sun will then become increasingly unstable. Over the following few hundred thousand years it will pulse about four times, like a lightbulb on the blink, only a little brighter each time, before it finally blows.

The Sun is too small to turn into a supernova when it explodes, and only a small fraction of its mass will blast away into space. The rest will shrink to a superdense core about the size of the Earth – an ultra-crushed ball made mostly of carbon and oxygen. This core will emit intense ultraviolet light which will make the expanding bubble of gas from the explosion glow mostly green and red. For a few tens of thousands of years this remnant will be surrounded by a planetary nebula as beautiful as any of the marvels[30] visible today. It may be a moment comparable to the penultimate bar in Handel's 1713 *Eternal Source of Light Divine* when, after the conclusion of the duet with voice, the trumpet rises to a top D, the tonic, at a pitch not previously reached in the piece.

After that, the gas bubble will disperse and, with no fusion taking place in the core, the Sun will remain a white dwarf about the size of the Earth today. Tiny contractions under its own gravity will be enough to generate light for many trillions of years until it becomes a black dwarf – a remnant that emits no heat or light at all. (The feel of this, as far as human imagination can extend, may be something like the adagio of György Kurtág's 1994 piece *Stele*.) The most likely fate of the black dwarf that was once our Sun will be that, after around 10^{19} years, it will be ejected (together with the remaining bound planets) from the galaxy into intergalactic space. If this doesn't happen then it may collide with another black dwarf in about 10^{21} years and produce a Type Ia supernova explosion that will destroy whatever remains of the solar system. If neither of these things happens, the black Sun will continue to orbit the galaxy, slowly falling towards the black hole at its centre. But before it can get there – in about 10^{100} years – the black hole will have evaporated. In this eventuality, the Earth will finally spiral into what was once the Sun – unless some unpredictable gravitational interaction knocks it out of our Sun's orbit into the depths of a cold, empty universe. Here, at no extra charge, is your cut-out-and-keep guide to the past, present and future of the Sun:

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MS  MS  MS  MS  MS  MS*MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
MS  MS  MS  MS  MS  MS^MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MSxMS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
MS  MS  MS  MS  MS  MS  MS  MS  MS  MS
RG  RG  RG  RG  RG  RG  RG  RG  RG  RG
h CHB o
WD  WD  WD  WD  WD  WD  WD  WD  WD  WD
WD  WD  WD  WD  WD  WD  WD  WD  WD  WD
WD  WD  WD  WD  WD  WD  WD  WD  WD  WD
```

(repeat thousands of times)

BD *ad finem*

Each pair of capital letters represents 100 million years in the life of the Sun. 'MS' stands for 'main sequence'. The beginning of life on Earth is marked by * at between 600 million and 700 million years after the formation of the solar system (and about 4 billion years before the present). The ^ is for 'you are here', and the x marks the likely end point of Earth as a viable home for life as we know it. 'RG' stands for 'red giant' and 'CHB' for 'core helium burning' (although this will last less than 100 million years). If the typeface for RG was proportional to MS in the same way that a red giant is proportional to a main sequence star each letter would be the best part of a metre high. The 'h' is the helium flash and the 'o' represents the tens of thousands of years in which the Sun is a planetary nebula. 'WD' is for 'white dwarf', 'BD' for 'black dwarf'.

Dark wonder: neutrino

'The light tells us much,' said the nineteenth-century nature writer Richard

Jefferies, 'but I think in the course of time still more delicate and subtle mediums will be found to exist, and through these we shall see into the shadows of the sky.' Beyond the light there are many kinds of darkness at the edge of knowledge.

Invisible light was discovered by William Herschel in 1800. He noticed that a thermometer placed in darkness just beyond the edge of the red light of a rainbow pattern projected by a prism heated up, and he concluded, correctly, that this was caused by 'calorific rays' – or what we now call infrared light. And it turns out that only a little over forty per cent of the photons hitting the Earth's surface are in the part of the spectrum visible to humans. Infrared and ultraviolet light make up almost all of the rest, with more than fifty and less than five per cent respectively. All three are important to life on Earth. Most significantly, perhaps, infrared light helps keeps the planet warm enough for life as we know it. Some snakes can detect infrared light[31] – heat emitted by their prey – while many birds and insects can see into the ultraviolet part of the spectrum. This gives a richness to their perception of colour that is hard for us to imagine – enabling them, for example, to see things such as patterns in the petals of flowers which are invisible to us. But there is something else even stranger than light pouring from the Sun, and it is entirely hidden from us.

Neutrinos, like photons, are elementary particles generated during fusion in the core of the Sun, as well as by other events in the universe. But, unlike photons, neutrinos pass straight through us with no discernible effect. Escaping instantaneously from the Sun without any of the delay experienced by photons, and travelling at fractionally less than the speed of light, trillions of them are flying through you every second. Even at night neutrinos from the Sun are whizzing through you, but this time from below, having first passed through the Earth. To neutrinos we may as well be ghosts.

Neutrinos were dreamed of before they were detected. In 1930, seeking to explain the conservation of energy and momentum when a proton is transformed into a neutron (a phenomenon called beta decay), the physicist Wolfgang Pauli found that he needed to posit the existence of an entirely new, invisible and hitherto unimagined particle. It was a wild idea at the time, and neutrinos themselves are no less strange. For one thing they are amazingly small – a tiny fraction of the mass of the next least massive elementary particle, the electron. For another, once created they interact with very little else. It would take, for instance, an average of a thousand light years (9,500 trillion kilometres) of lead to stop one. That's just the average, however, and very occasionally a neutrino will strike an atom in a much less massive and dense object. It is by detecting these rare events that we know for sure that they exist.

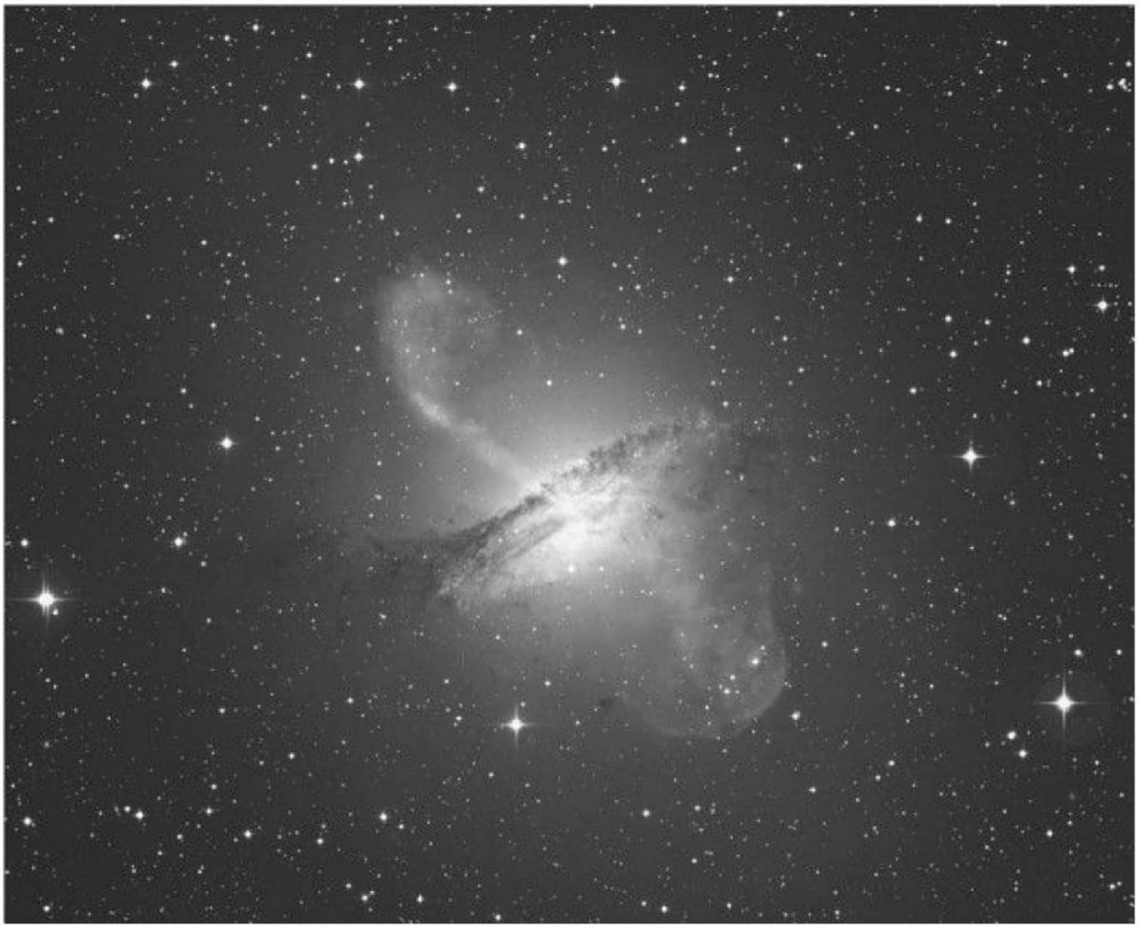
The first neutrinos were observed in the 1950s. They came not from the Sun but from the explosions of supernovas – massive stars at the end of their lives – in deep space. When a typical supernova explodes[32] it unleashes an octodecillion, or 10^{57}, neutrinos. The Sun's neutrinos were not detected until the 1960s, when a physicist who shares his name with *Kinks* frontman Ray Davis oversaw the construction of a 'telescope' consisting of a hundred thousand gallons of cleaning fluid deep in an old mine in South Dakota. On average, one neutrino each day would interact with an atom of chlorine in the fluid, turning it into an atom of argon. Amazingly, Davis worked out a way to find the argon.

But there are even stranger things about neutrinos than their tiny size and their elusiveness. One is their changeable nature. The type, or 'flavour', of a given neutrino is never fixed. Instead, it oscillates between three different states as it flies through space. If a neutrino does interact with ordinary matter, it converts into one of three different types of charged particles with different properties depending on which part of its oscillation it happens to be in. Another mystery is the question of how neutrinos (unlike photons) have mass. According to the Standard Model of particle physics, particles must exist in both 'left-handed' and 'right-handed' versions if they are to have mass. But only left-handed neutrinos have been observed – a riddle to match the koan about the sound of one hand clapping. A solution to this, if there is one, may help reveal why is there more matter than antimatter in the universe.

Dark wonder: black holes

Another darkness at the edge of understanding concerns the nature of black holes. One way these celebrated anti-objects come into being (or non-being) is when a star of sufficient mass – typically more than about twenty-five times that of the Sun – burns up all its fuel and, with fusion no longer pushing energy outwards, collapses in on itself. It then explodes as a supernova, flinging electromagnetic radiation and neutrinos into space in huge quantities; but at the same time, the core collapses inwards until it becomes a singularity: a region where matter is infinitely dense and space-time is infinitely curved. At this stage the laws of physics as we know them run into trouble. General relativity predicts black holes, but quantum mechanics predicts something called Hawking radiation[33] at their event horizons (the boundary between the black hole and the rest of the universe) – a phenomenon that appears to be incompatible with general relativity. At any rate it is unclear how to reconcile the two. The puzzles go further, and have led physicists to astonishing hypotheses. Some have suggested that black holes may end their lives by transforming into their exact opposite – ‘white holes’ that explosively pour all the material they ever swallowed back into space. Others have argued, variously, that our universe could look like a black hole to people in another universe; that new universes are continually being created within black holes; and that a hyper-black hole spawned our universe – meaning that the Big Bang was a mirage created by a collapsing higher-dimensional star. Yet others have computed the internal energy of a black hole, the position of its event horizon and other properties to indicate that gravity arises from infinitely thin vibrating strings which exist in ten dimensions, with our universe merely a ‘hologram’.

Some black holes also create the brightest known objects in the universe. They spin, and in doing so they twist the encircling space-time around themselves, creating a maelstrom around an infinitely thin ring instead of a point. This pulls the mass of nearby gas, dust, stars and planets from the surrounding galaxy towards them, setting them spinning, accelerating them and tearing them apart, and in the process, they create vast magnetic fields and enormous heat. The magnetic fields shoot jets of particles out into intergalactic space at right angles to the plane of rotation, and at close to the speed of light, for thousands and sometimes millions of light years. If the black hole is massive enough, the gravitational shearing and friction in its accretion disc can produce more heat and light than anything else in the universe. This is called a quasar and its radiation covers the entire electromagnetic spectrum, from radio waves and microwaves at low frequencies, through infrared, ultraviolet and X-rays, to high-frequency gamma rays.

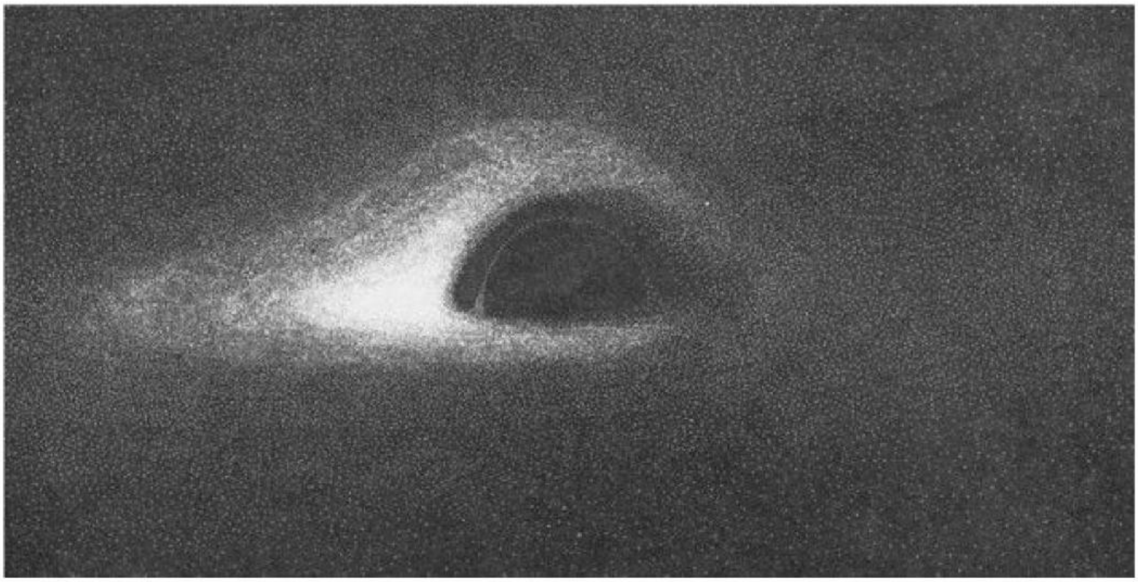


In the giant galaxy Centaurus A (NGC 5128), jets ejected perpendicular to its plane are signatures of a supermassive black hole at its centre.

The brightest known quasar, memorably named S5 0014+81, is three hundred trillion times brighter than the Sun, or more than twenty thousand times brighter than all the stars in the Milky Way galaxy combined. At the quasar's centre is a black hole 40 billion times the mass of the Sun and about ten thousand times more massive than the black hole at the centre of our galaxy. Actually we should say 'was', because S5 0014+81 is over twelve billion light years away, so telescopes show it to us as it was more than twelve billion years ago.

At the time of writing, every image of a black hole is a product of human ingenuity and imagination rather than a picture of the real thing. The rendition in the 2014 film *Interstellar*, created with the help of the physicist Kip Thorne, shows a funnel or sphere of absence that bends the light from the stars behind it and to its sides (a phenomenon called gravitational lensing), and is surrounded by a glowing accretion disc of gas around its equator which (by the same lensing effect) appears to bend into a 'rainbow of fire' across its top. This is probably a fairly accurate representation of at least part of what you would see, except that the light around a spinning black hole would appear much brighter on the side turning towards you than on the side turning away, creating an effect more like a smooshed crescent moon than a halo. Thorne deliberately avoided this asymmetry, fearing it would confuse cinemagoers, but it can be seen clearly in an image created back in 1978 by the astrophysicist, writer and poet Jean-Pierre Luminet. Employing what was already a long-obsolete 1960s IBM 7040 computer which used punch cards, Luminet had no way to visualize the results on a screen so he used the data to draw an image by hand, putting individual dots of India ink onto a photographic negative.

It may be that astronomers will have captured the first actual pictures of a black hole by the time you read these words. The technical challenge is enormous: the nearest black hole is thought to be hidden in a bright and compact astronomical radio source called Sagittarius A* about 26,000 light years away in the centre of our galaxy. At that distance it is about as big as a bagel on the surface of the Moon, and it will require a telescope with a resolution more than a thousand times better than the Hubble Space Telescope to produce an image. As this book went to press, a global collaboration called the Event Horizon Telescope had created just that. With radio-telescopes distributed from Hawaii to Spain, and from Arizona and Chile to the South Pole, it is hoping to create from their pooled data what would in effect be a single telescope with an aperture as wide as the diameter of the Earth.



Black hole by Jean-Pierre Luminet (1978).

Other techniques are likely to greatly increase understanding of black holes and in turn the capability to visualize them. In 2016 a team of nearly a thousand scientists astonished and delighted almost everybody by recording a ‘bleep’ thought to be caused by the merger of two black holes 1.3 billion light years away. The Laser Interferometer Gravitational-Wave Observatory, or LIGO – an apparatus consisting of two sets of two four-kilometre-long arms set at right angles to each other and located nearly five thousand kilometres apart – recorded a change in the position of one array with respect to the other by a ten-thousandth the diameter of a proton. It was equivalent to measuring a change in distance to the nearest star by the width of a hair. With their findings, the team confirmed the existence of gravity waves – ripples in the curvature of space-time that propagate at the speed of light and were first predicted by Einstein a hundred years ago. They also created a simulation of the supposed cause of the bleep – an animation in which two black holes circle each other ever closer and faster until suddenly they merge into one, like bubbles meeting in the vortex above a plughole. In future, LIGO and systems that exploit the same principles are likely to make it possible to investigate black holes, neutron stars and other ‘dark’ phenomena with even greater precision and detail. Astronomers will increasingly listen[34] as well as look at the universe.

Black holes are not the only kinds of darkness at the edge of understanding. If some theories are right, dark matter and dark energy are also on that horizon. Together, these two are thought to account for more than 95 per cent of all the mass and energy in the universe, and yet both currently escape direct detection. Dark matter does not interact with any part of the electromagnetic spectrum and is therefore invisible. Its existence is inferred from gravitational effects – notably, from the fact that galaxies move more quickly and create greater distortion through gravitational lensing than the ordinary matter in them can account for. Similarly, the existence of dark energy is inferred only from its effect, which is to accelerate the expansion of the universe. A leading hypothesis on the nature of dark matter, at least until recently, has been that it is composed of weakly interacting massive particles, or WIMPs, that exert influence only through gravity and the weak nuclear force. This idea has proved to be extremely successful in accounting for the observed history of the cosmos. But the failure, so far, to find any trace of these particles has raised doubts. Perhaps, it has been suggested, dark matter is a superfluid: a Bose-Einstein condensate that could account for quantum entanglement (or what Einstein called ‘spooky action at a distance’), which, being instantaneous, seems to be faster than light (though it may, in fact, be more meaningfully characterized as existing outside time). Some physicists now doubt that dark matter and dark energy actually exist, suggesting that theories such as Modified Newtonian Dynamics, in which gravity no longer weakens with distance, will account for observed effects. Future research may tell. For now, we may be almost as much in the dark as those who, thousands of years ago, wondered about the nature of light.

Many other questions are yet to be answered. What, for example, lies in darkness beyond the edge of the visible universe? Is there an infinite extension of the same – ever more galaxies arranged into a cosmic web of stupendous beauty? Or is the universe as we know it ultimately limited in extent – although, like the surface of a sphere, unbounded? If the latter is the case then could our universe, of which we see only a small part, be one bubble among many?

Henry Thoreau describes walking on a November day just before dark when the Sun breaks through grey cloud, and the land, touched with 'such a light[35] as we could not have imagined a moment before', becomes a paradise. For Thoreau, the fact that these same conditions will recur on an infinite number of evenings in the future makes it more glorious still. His sentiment is easy to share: the Sun may be finite within a cosmological time frame, but measured against the scale of human history it is unending.

On the morning in early October when I write this, unusually bright sunshine pours down. Almost a month has passed since a day on which I last stepped into light of comparable brilliance, wheeling my father, who had been close to death, out of his hospital ward into the open air. Rising briefly from the oblivion[36] into which he had almost disappeared, he said how beautiful it was. Today, again, it feels like the dearest, most wonderful gift. 'I cannot understand time,' wrote Richard Jefferies. 'It is eternity now.[37] I am in the midst of it. It is about me in the sunshine.' The deep sky above me must be what the nineteenth-century art critic John Ruskin called a visible heaven, and I stand here, hoping to store some of its strength for the dark months ahead.

'Half our days we pass in the shadow of the earth,' wrote the seventeenth-century physician Thomas Browne, 'and the brother of death exacteth a third part of our lives.' For we the living, sleep[38] is the death of each day's life, but on the morrow, governed by the circadian rhythms that our ancestors have followed since the Proterozoic, we wake and the morning light is a daily grace. Light from the kind old Sun cannot restore the dead to life (although the near-infrared part of its spectrum can help heal wounds and relieve pain). One day the Sun itself will die. For now, it shines in glory and allows us to see the light in the eyes of other waking souls.

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1 If the speed of light really were infinite, particles and the information they carry

would move from A to B instantaneously, cause would sit on top of effect and everything would happen at once. The universe would have no history and no future, and time as we understand it would disappear.

2 In reality not all the moons of Jupiter are impassive orbs. Io, which is about the same size as our Moon, is dotted with volcanoes the size of Everest and is the most volcanically active body in the solar system. Enceladus, a small moon unknown to Galileo, spouts water though its icy crust.

3 'A photon is a minimal disturbance in an electromagnetic field ... Quantum theory [states] that energy comes in discrete units or quanta. Because these units cannot be broken down further they have the sort of integrity we associate with particles, and in some circumstances it is helpful to think about them that way. In that sense, photons are particles of light.' Frank Wilczek

4 The strong nuclear force binds protons and neutrons together into atomic nuclei. The weak nuclear force is responsible for radioactive decay and nuclear fission.

5 We never see the world as our retina sees it, says the neuroscientist Stanislas Dehaene. 'In fact, it would be a pretty horrible sight: a highly distorted set of light and dark pixels, blown up toward the centre of the retina, masked by blood vessels, with a massive hole at the location of the 'blind spot' where cables leave for the brain; the image would constantly blur and change as our gaze moved around. What we see, instead, is a three-dimensional scene, corrected for retinal defects, mended at the blind spot, stabilized for our eye and head movement, and massively reinterpreted based on our previous experience of similar visual scenes.

6 To be more specific, the peak absorption frequencies for the different kinds of cone cells in our eyes are: 564nm, which is towards the redder end of the spectrum but is actually yellowish-green; 534nm, blueish-green; and 420nm, blueish-violet.

7 'The word is blue at its edges and in its depths. This blue light is the light that got lost' Rebecca Solnit

8 'Light is something like raindrops.' Richard Feynman

9 The account of the rainbow in Genesis is in turn shaped by older stories such as the one that appears in the *Epic of Gilgamesh* (*c*.1800 BC), which tells how the goddess Ishtar lifted a jewelled necklace into the sky as a promise that she would never forget the great flood that destroyed her children.

10 Raindrops are usually between 0.1 millimetres and 5 millimetres across. They are shaped like oblate spheroids – that is, spheres with squashed noses. In the foggy conditions that create a 'ghost rainbow' the drops are so small that quantum mechanical effects become important and smear all the colours to white.

11 The law of refraction describes the relation between the angles of incidence and refraction when light passes between different mediums such as air and water. It was discovered by Ibn Sahl around 984, and then rediscovered by Thomas Harriot in 1602 and Willebrord Snel in 1621.

12 As the novelist Philip Pullman explains, single vision for Blake is a literal, rational, dissociated and unemotional view of the world. Twofold vision sees not only with the eye but through it to contexts, associations, emotional meanings,

connections. Threefold vision is the place of poetic inspiration and dreams, while fourfold vision is a state of ecstatic or mystical bliss.

13 'The short night – on the hairy caterpillar beads of dew.' Buson

14 '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.' Isaac Newton

15 Going on appearances, Philip Larkin would seem to be to lyric poetry is what Eddie the Eagle is to ski-jumping. But Larkin's 'Water', in which he imagines a new religion, shows otherwise:

'My liturgy would employ
Images of sousing,
A furious devout drench,
And I should raise in the east
A glass of water
Where any-angled light
Would congregate endlessly.'

16 When viewed in ultraviolet, the rings of Saturn, which are made of water ice, appear as a strange rainbow of reds, pinks, turquoises, deep blues and other colours.

17 You can almost hear the drops in György Kurtág's 'Play with Infinity' (1973) or in György Ligeti's étude 'Arc-en-Ciel' (1985–2001).

18 The year 2016 was the hottest in human history, and a new high was reached for the third year in a row, bringing the global average temperature to 1.2ºC above pre-industrial levels. It is likely that climate change resulting from human emissions of greenhouse gases will significantly increase future storm intensity and frequency.

19 'In general relativity, bodies always follow straight lines in four-dimensional space-time, but they nevertheless appear to us to move along curved paths in our three-dimensional space. This is rather like watching an aeroplane flying over hilly ground. Although it follows a straight line in three-dimensional space, its shadow follows a curved path on the two-dimensional ground.' Stephen Hawking

20 Other planets in the solar system also cast light on their moons. Saturnshine has been photographed with great clarity on its moons Dione and Mimas. A grainy image shows Plutoshine on its moon Charon.

21 A legend of the Yurok Native Americans says that far out in the Pacific Ocean, but not farther than a canoe can paddle, the rim of the sky makes waves by beating on the surface of the water. On every twelfth upswing, the sky moves a little more slowly, so that a skilled navigator has enough time to slip beneath its rim, reach the outer ocean, and dance all night on the shore of another world.

22 Zodiacal light is, in the astronomer Caleb Scharf's words, 'a dusty impression of the alignment of the planets in their huge disk of orbital paths, and of all the other objects sharing this same space'.

23 Helium accumulates as a stable end product when uranium decays into lead. A kind of alchemy turns the source material for nuclear bombs into the stuff of the Sun and the element most protective against radioactivity.

24 In reality, fusion is a complex, multistep process. The closer the two protons get, the more strongly their positive charges push them apart. Only an effect known as quantum tunnelling enables them to bond. It is as if they don't have enough energy to open the door and walk through, but will occasionally teleport straight through a wall. Further, the helium-2 produced when two protons do bond is extremely unstable and usually splits back into two separate protons. One time in ten thousand, however, one of the protons will spontaneously transform into a neutron, and the atom then becomes deuterium, a stable isotope of hydrogen. Deuterium and hydrogen can fuse to make a stable form of helium, and it is this that releases the energy that powers stars.

25 You may think that 'plasma' is a hard word to rhyme, but the band They Might Be Giants manage it in 'Why Does the Sun Really Shine?': their solution was 'miasma'.

26 The Sun is not the only cause of auroras in the solar system. In the case of Jupiter's moon Io, a green, red and blue aurora is caused by interaction with the magnetosphere of the giant planet rather than with our star.

27 'Stars, like thoughts, are not inevitable. Out of the diffuse disorder something may or may not coalesce, and floating specks in space find each other very escapable.' Amy Leach

28 David Bedford tried it in *Star's End* (1974), but it's not an easy listen. For the Sun's main sequence, Brian Eno's *Lux* (2012) could be a starting point. Or, encompassing all, *Sun Star* by John Coltrane (1967).

29 The last complex multicellular life on Earth less than a billion years from now may be, or resemble, tardigrades – the 'water bears' that subsist on bacteria and on smaller tardigrades – and/or something like the tubeworms found at hydrothermal vents on the ocean floor. Microbes may persist deep within the Earth for another 2 billion to 3 billion years.

30 One of the most beautiful nebulas, the Ring (M57), is a circular rainbow with a sky-blue centre surrounded by green, orange and then red. Planetary nebulas play a significant role in galactic evolution, expelling heavy elements such as carbon and nitrogen forged from hydrogen and helium by their parent stars into the interstellar medium where they become part of the next generation. The carbon in every living thing on Earth probably comes from nebulas like these.

31 In certain circumstances, humans can see some infrared light. It happens when pairs of infrared photons 'double up' and hit the same pigment protein in the eye at the same time. Subjects report seeing infrared light from a low-energy laser.

32 There is, on average, one supernova explosion per galaxy per century. In the observable universe about a billion explode every year. That is, thirty per second. The universe bubbles like champagne.

33 A simplistic description of Hawking radiation goes something like this: every cubic millimetre of space in the universe, no matter how empty it seems, is actually a chaotic arena of fluctuating fields, with pairs of particles and anti-

particles such as positrons and electrons flickering in and out of existence. (To adapt Heidegger, *das Nichts etwast*, or 'the nothing somethings'.) Normally, the particle–antiparticle pair annihilate each other within about a billionth of a billionth of a second. But near the horizon of a black hole it's possible for one of the pair to fall in before the annihilation can happen, in which case the other escapes as Hawking radiation.

34 Electromagnetic waves can also be observed by artificially transforming them into sound waves. The astrophysicist Wanda Diaz Merced, who became blind in her twenties, investigates the energy and light released by gamma-ray bursts, the most violent events in the universe, by transforming light curves and data sets into sound. By listening to variations in pitch, duration and other sound qualities, she decodes patterns in burst-like interstellar light.

35 'late sunlight enters the deep wood, shining over the green moss again.' Wang Wei

36 When you descend more than about two hundred metres below the surface of the sea, the water is said to turn the deepest blue imaginable, described by the deep-sea pioneer William Beebe as 'luminous black'.

37 For a particle of light, or photon, this is literally true. Time stands still such that past, present and future all collapse down to one eternal moment.

38 'The unfathomable deep
Forest where all must lose
Their way.'
Edward Thomas

2

THE GATHERING OF THE UNIVERSAL LIGHT INTO LUMINOUS BODIES

Life

The world, though made, is yet being made …This is still the morning of creation.

John Muir

Life is a self-sustaining chemical system capable of incorporating novelty and undergoing Darwinian evolution.

Gerald Joyce

It rains the same old rain, the same old rain that it rained on the dinosaurs.

Nick Cope

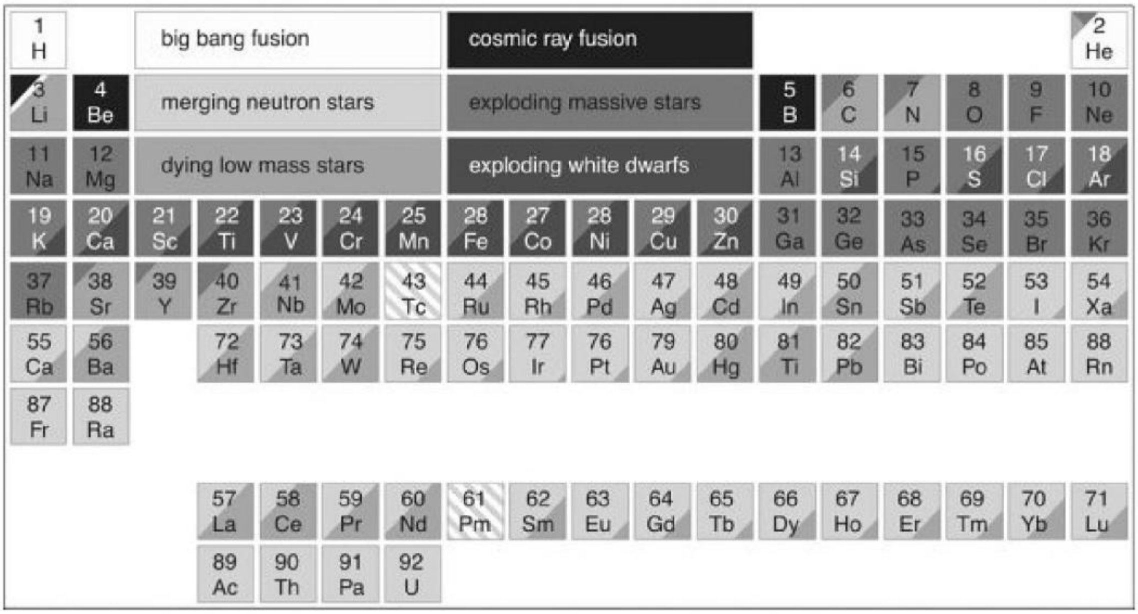
later, in a process called primordial nucleosynthesis, the nuclei of what would become hydrogen and helium began to coalesce from these protons and neutrons. As the universe continued to expand and cool, things began to happen more slowly. By 380,000 years after the Big Bang most electrons became bound in orbits around these nuclei, forming hydrogen and helium atoms. And, with electrons now bound into atoms, photons were able to travel freely. This was the time of first light, and its trace is still visible as the cosmic microwave background.[5]

Millions of years later, as the universe cooled further, gravity began to pull together stars[6] and galaxies out of clouds of molecular gas. Over time and ever since, heavier elements such as carbon, oxygen, nitrogen and iron have been forming, transmuting continuously in the alembics of successive generations of stars. In the triple-alpha process, which takes place inside main sequence stars, three helium atoms (which have two protons and two neutrons each) are transformed into a carbon atom (six protons and six neutrons), which may then fuse with an additional helium atom to produce oxygen (eight protons and eight neutrons). In the explosive stages towards the end of a star's life, it forges elements of increasing atomic mass all the way up to iron (twenty-six protons and, typically, thirty neutrons).

If a star is massive enough, the collapse leads to a rebound and to the explosion called a supernova, which briefly outshines an entire galaxy, radiating as much energy in weeks or months as an ordinary star such as our Sun does in billions of years. The pressures and temperatures in the short period before a supernova fades vastly exceed anything during the star's previous existence, and produce lots of iron, as well as more massive elements, including at least one – iodine (fifty-three protons) – which is also essential to life as we know it. Phosphorus, another element essential to life, is made in especially large supernovas called hypernovas. Boron – an element that plants (and possibly animals) need – is created when cosmic rays, which are the highest-known energy particles in the universe and which originate in massive explosions of this kind, strike a heavier element and blow it apart. Gold, which is in the nice-to-have rather than the essential-to-life category, is probably made in the ultraviolent collision of neutron stars, the densest-known things in the universe short of black holes.

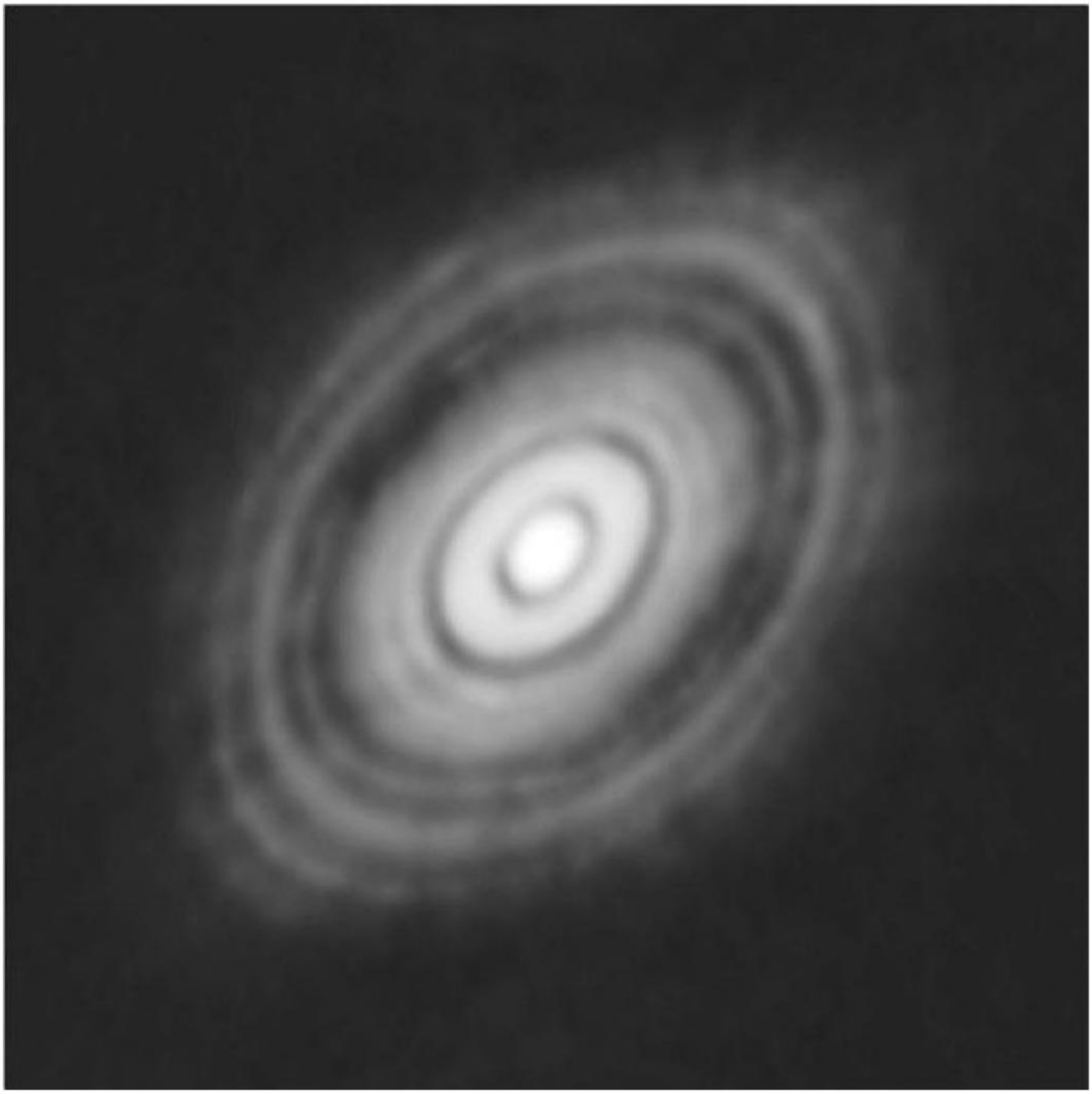
As supernovas and hypernovas explode, they hurl the elements they have created across space into the interstellar medium – a 'mist' that is mostly hydrogen and helium but also one part in a hundred heavier atoms. The mist is thin – at about one atom per cubic centimetre, a more complete vacuum than has ever been achieved on Earth – but it is a hundred thousand times denser than the space between galaxies. And where it is relatively concentrated in molecular clouds, the constituents begin to exert mutual gravitational attraction and sometimes draw together enough material to collapse into a new generation of stars and planets.

The Origin of the Solar System Elements



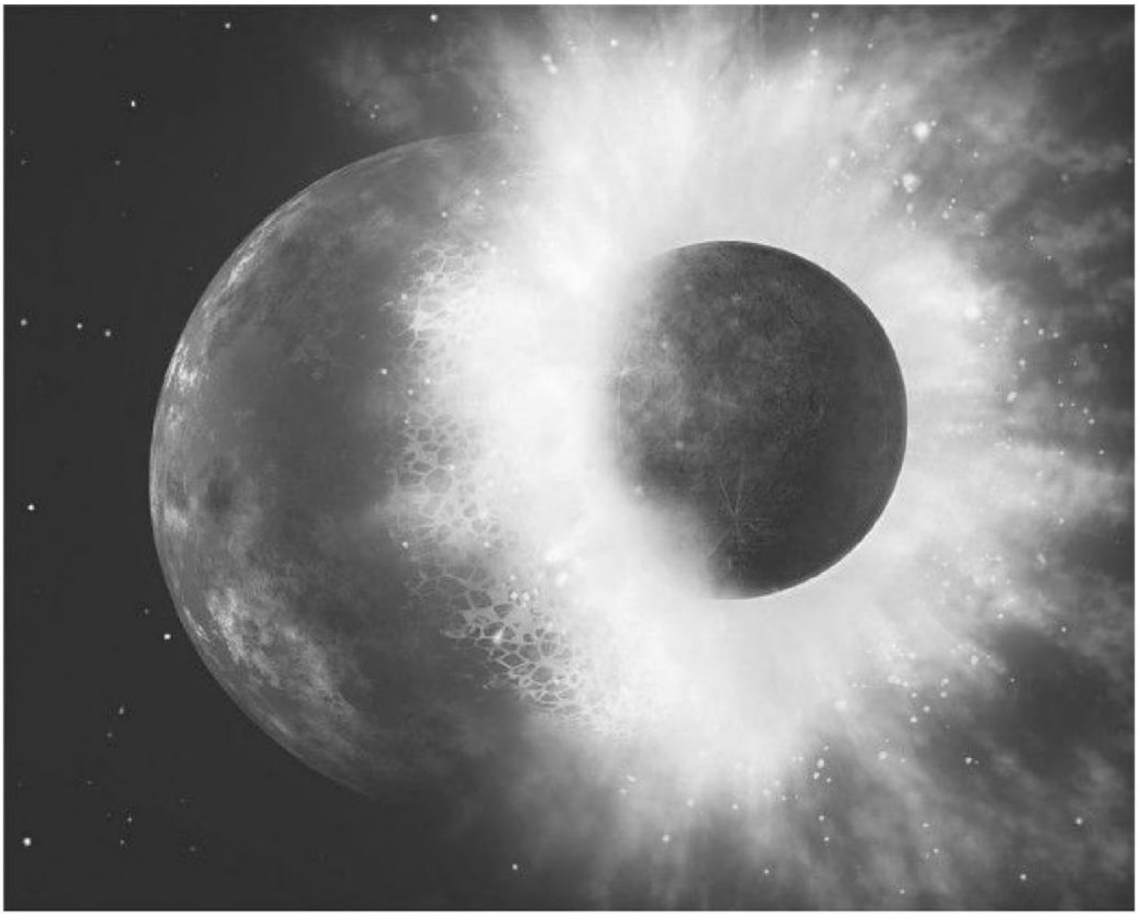
The elements in our solar system were made in collapsing, merging and burping stars as well as exploding ones.

The story of the Earth begins around 4.6 billion years ago when the 0.04 per cent of the mass of solar system that was not a part of the Sun formed a disc of dust around it. Amazingly, astronomers have recently photographed a protoplanetary disc that probably looks like ours did at that time. HL Tauri, which is about 450 million light years away from Earth, is only about a million years old (as we see it), but already its disc appears to be full of forming planets. And it was from such a disc that the proto-Earth, which some call Tellus, first formed out of the debris into a sphere about the size of Venus, or a little smaller than the Earth today. Then, some tens of millions of years later – according to the giant impact hypothesis – another planet about the size of Mars, which astronomers call Theia after the Greek goddess who was mother of the Moon, struck the Earth in what is now thought to have been a head-on collision rather than a glancing blow. The impact by an object about a tenth of the Earth's present mass released about a hundred million times more energy than the Chicxulub impact that wiped out the dinosaurs, and it was enough to melt both planets and mix them together. Think of the punches to the face taken by Robert De Niro as Jake LaMotta in *Raging Bull* and then some. A great chunk sheared off to become the Moon, while the remaining mass quickly regained its spherical shape because of gravity. The blow had, however, tilted the axis of the planet to a 23.5° angle – giving rise, ultimately, to what we know in high latitudes as the seasons.



A protoplanetary disc around the star HL Tauri..

All this took place at the beginning of Earth's first eon, the Hadean, which lasted from 4.54 billion to 4 billion years ago. The name, familiar to many as Hades for the Greek underworld and its god, actually derives from a word for 'the unseen', and this is particularly appropriate because the enormous stretch of Hadean time has left next to no visible traces. Unseen does not, however, mean completely unknowable, and researchers can construct plausible scenarios for the momentous changes that must have taken place – making reasonable inferences to suggest subdivisions to the eon with names such as the Procrustean and the Promethean.[7] A detailed animation or a virtual-reality production based on these deductions would be at least as compelling as anything in Terrence Malick's *Voyage of Time* or Werner Herzog's *Into the Inferno*.



Hypothesized impact of Theia on Earth

Initially, a thick cloud of intensely hot vaporized rock surrounded the reformed Earth, but after a few thousand years this cooled and condensed, and as little as 10 million years later the planet itself had cooled enough for rock to form a solid surface crust mostly covered by liquid water and surrounded by an atmosphere composed largely of nitrogen and carbon dioxide. But the Earth was not out of the wars yet. In a period known as the Late Heavy Bombardment, from about 4.1 billion to 3.8 billion years ago, it was probably hit repeatedly by planetesimals of various sizes. Thousands of them were around twenty kilometres across – tiny compared to Theia, but much bigger than Chicxulub. A few may have been five hundred kilometres or more across: big enough to vaporize huge regions of the Earth's rocky surface and to evaporate much or even all of the ocean, leaving only molten salt behind. If you could have seen through the opaque atmosphere, the sight might have resembled the desolation that Moomintroll and his friends find on the seabed in Tove Jansson's *Comet in Moominland* when the ocean burns away. Within a few thousand years of each impact, however, the atmosphere would cool again and rains of unimaginable intensity would refill the oceans.

Our view of the origin of life is as cloudy as a sky in the late Hadean or the early Archaean (the eon that succeeded it). But one thing is sure. Stepping onto this planet about four billion years ago would have been quite an experience. The Earth spun much faster than today, and night followed day every five or six hours. The stars were seldom visible because the atmosphere was full of smoke and dust, but spectacular shooting stars regularly whizzed through the sky. The Sun, when it could be seen at all through the smog, shone weakly. The Moon[8] was only about a third of its present distance from the Earth, and it would have looked huge, with an apparent diameter almost three times larger and an area eight times larger than today.

Imagine standing on the rocky shore of a volcanic island at this time. At about seventy degrees centigrade, the air is hotter than Death Valley but cooler than a sauna.[9] The atmosphere is mostly nitrogen and carbon dioxide. You need both a cooling and a breathing apparatus. In the distance, you can see other islands rising from the sea, some of them active volcanoes. The rocks beneath your feet are made of dark larva, and volcanic ash fills the crevices. Hot springs boil nearby. The sea water has a greenish tint from all the unoxidized iron it contains. White deposits of dried salt on the lava rocks show where small tide pools have evaporated. Freshwater ponds a few metres above the beach are constantly being filled by small streams of rainwater cascading down the hillside, then drying out in the heat. Suddenly the landscape is brilliantly illuminated as a blinding white streak silently crosses the sky and falls into the sea just over the horizon. An asteroid about a hundred metres across has penetrated the atmosphere at twenty kilometres per second and crashed into the ocean several miles away – one of many such impacts to occur every day. A thin dark line on the ocean advancing towards you is the resulting tsunami. If you move to higher ground in time and escape the flood you may live to witness the colossal tides, ebbing and flowing a hundred vertical metres or more, under the pull of the colossal Moon.

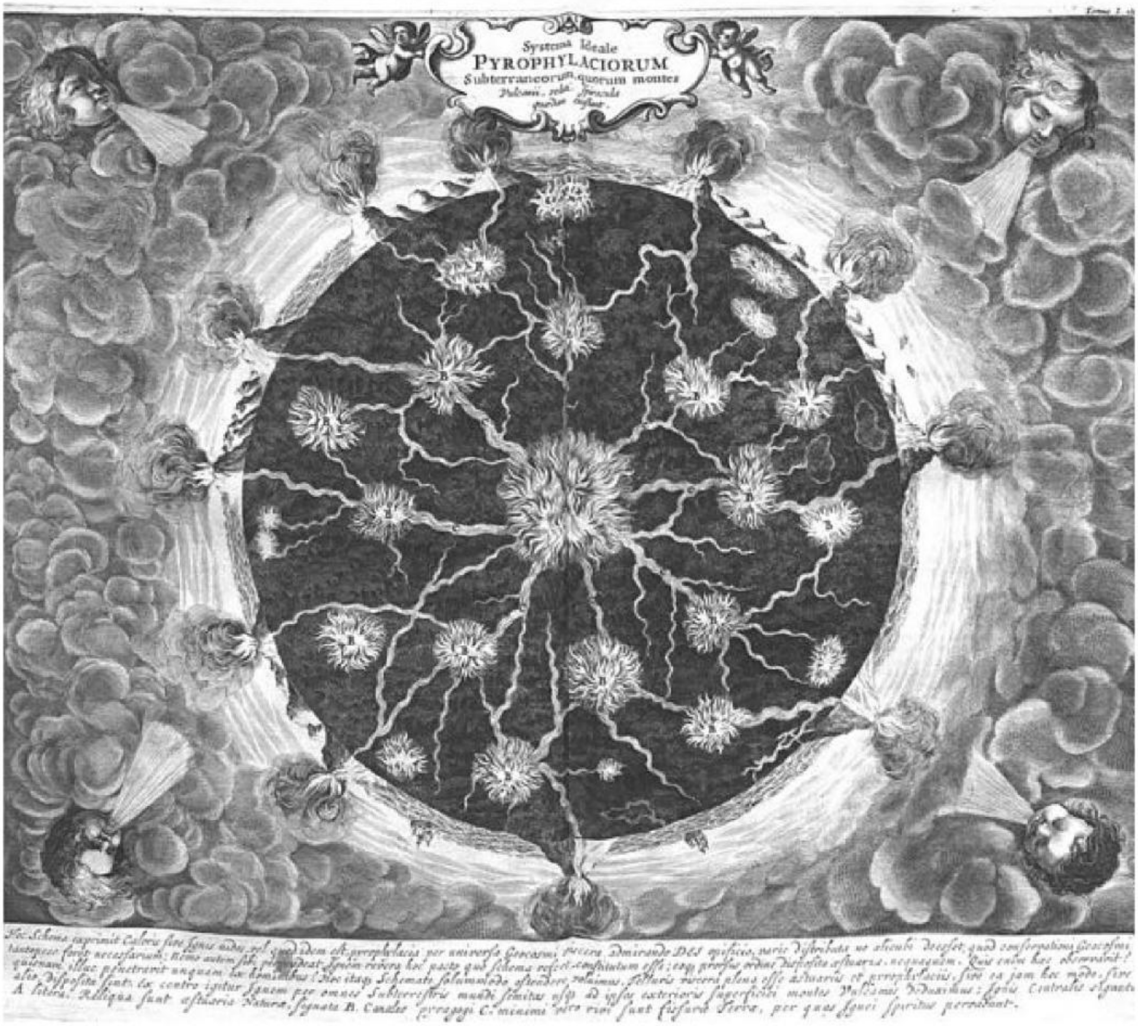
Water

'Like all profound mysteries,' wrote Nan Shepherd in *The Living Mountain*, her 1940s meditation on the Cairngorms, 'water is so simple that it frightens me. It wells from the rock, and flows away. For unnumbered years it has welled from the rock and flowed away. It does nothing, absolutely nothing, but be itself.' Shepherd's vision is compelling but – in this passage at least – she overlooks a to be scarce – although there is, amazingly, ice at Mercury's southern and northern poles, permanently shaded in craters from daytime temperatures of over 400ºC. Venus may once have had abundant water but virtually all of it boiled away in a runaway greenhouse effect long ago. And the northern plane of Mars was once covered by a great ocean. When meteorites slammed into it, tsunamis more than 120 metres high swept over its shores. But that ocean evaporated into space billions of years ago and what water remains on Mars is, as far as we know, almost entirely ice. The ice caps at the poles of Mars, which were first spotted by Giovanni Cassini in 1666, have a combined volume a bit greater than that of the ice cap on Greenland. Significant amounts of ice also sit just below the surface in high latitudes and there are scattered patches of surface ice in mid-regions as well as a small frozen sea, equivalent in volume to the North Sea, near the equator. Mars has some glaciers too, but the flowing liquid water that was discovered in 2015 seems limited to a few trickles of thick brine in crater walls and gullies. For the most part the landscape is one of dry channels, canyons and craters, rocks and dust. The only seas are sand.

Earth is, of course, unique in the solar system[14] in that it is covered – seven-tenths of the surface to an average depth of four kilometres – in liquid water. For conditions favourable to life, our planet is the Goldilocks, while Venus is too hot and Mars too small. But the water on Earth's surface is only part of the story. Its presence in the planet's inward and nether parts[15] plays a key role in the origin of life.

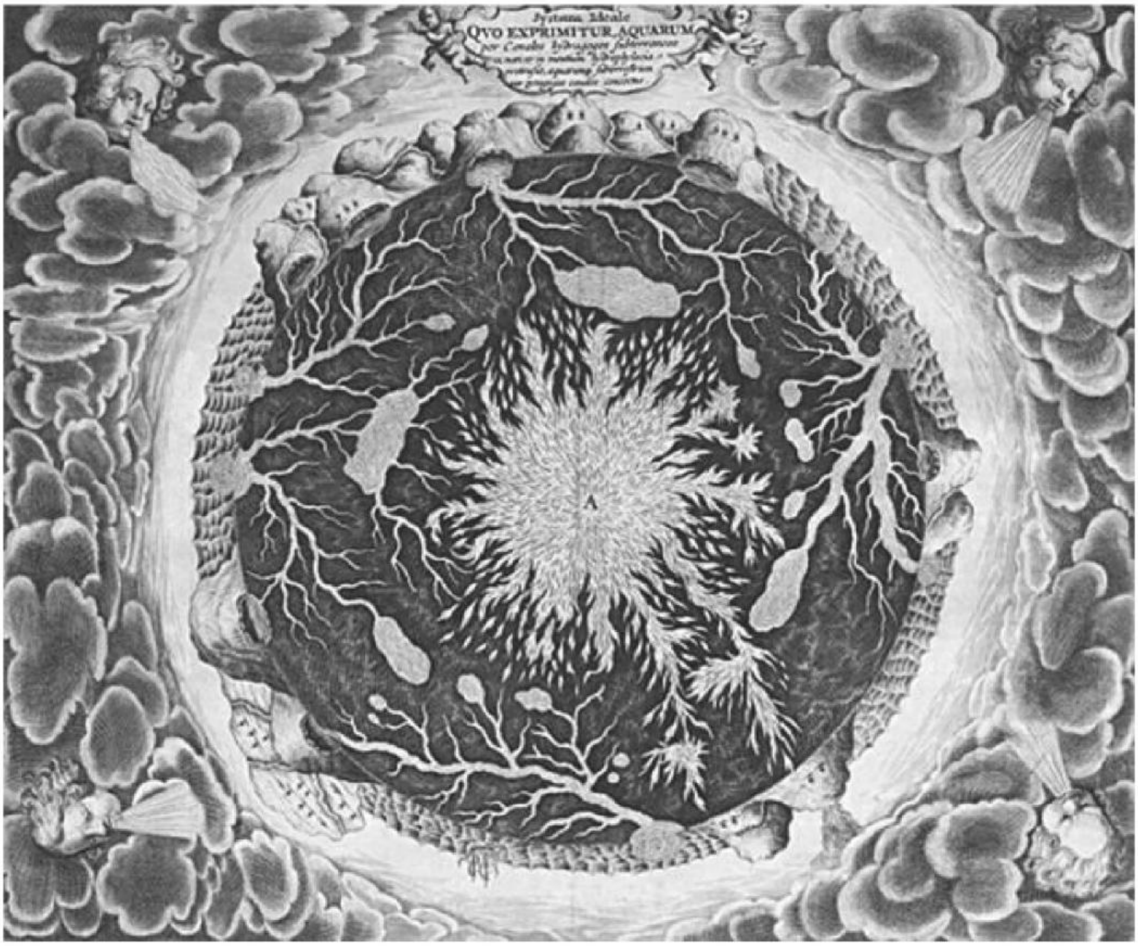
On an extended visit to Malta in 1635 a Jesuit priest and scholar named Athanasius Kircher was entranced by the island's inland sea and, in particular, by its caves and long natural passageways winding deep into the rock. Stopping over in Sicily on his way back to Rome in 1638, he witnessed phenomena which, together with his experience on Malta, were to shape his outlook for life. Sailing through the Strait of Messina, his party encountered a whirlpool that Kircher described as a 'vast hollow' and then watched, astonished, as Etna issued huge clouds of thick smoke that entirely hid the island. Putting ashore, they heard a noise resembling 'an infinite number of chariots driven fiercely forward' and soon after were thrown onto the ground by 'a most dreadful earthquake'. With 'universal ruin all around', his party continued along the coast by sea, finding 'nothing but scenes of horror', and saw the volcano island of Stromboli belching flames with a rumble that was clearly audible even though it was a hundred kilometres away. Terrible as these events were – thousands of people died – they only increased Kircher's fascination with the 'miracles of subterraneous nature' and how the phenomena he had seen in Malta and Sicily might be linked together.

Kircher went on to became a polymath – 'the master of a hundred arts', including a proposed cat piano that would play a different note by stretching the tail of a different cat for each key stroke. But among his greatest achievements is the *Mundus Subterraneus* (*Underground World*) a strange and beautiful work published in 1665 that laid out, along with much else, a theory of the deep workings of the Earth. Volcanism, Kircher proposed, was caused by the circulation of great fires in the 'hollowed rooms and hidden burrows' all the way down to the Earth's core. Volcanos were the 'fire-vomiting vent-holes, or breath-pipes of Nature'. In addition, he said, the tides pushed immense quantities of water through various 'hidden and occult passages at the bottom of the Ocean' and thrust them 'forcibly into the intimate bowels of the Earth'. Somewhere off the coast of Norway, he claimed, the sea drained down a huge maelstrom,[16] from where it ran through the Earth, which cooled it and provided it with nutrients, before being expelled through a nether opening at the South Pole. More than once, Kircher compares the movement of the Earth's water to the circulation of the blood in the body as described by his near-contemporary the physician William Harvey.



'Vulcan hath his elaboratories, shops and forges in the profoundest Bowels of Nature' *Mundus Subterraneus* (1665).

Though it was wildly wrong in many particulars (water does not, for example, rush in immense liquid flows deep inside the Earth), Kircher's vision was a step in the right direction. Volcanoes along the same plate boundary, such as Etna and Stromboli, *are* connected. And in the last few decades scientists have determined that, on a geological timescale, water *is* carried down beneath the Earth's crust into the mantle. Something like one to three oceans' worth is packed into rocks in the transition zone some 400 to 650 kilometres (and perhaps deeper[17]) below the surface, where the pressure exceeds a hundred thousand atmospheres and the temperature a thousand degrees centigrade. Carried there by subduction as one continental plate slides under another, the water makes rock more viscous, rather as adding liquid to a cake mixture can do. As we will see later in this chapter, this process is linked to the origin and continued existence of life on Earth.



‘The tides push an immense bulk of water through hidden and occult passages at the bottom of the Ocean, and thrust it forcibly into the intimate bowels of the Earth.’ *Mundus Subterraneus* (1665).

You have to go very deep indeed[18] to get to a place with no water. And even the Moon, which at first sight is as dry as a bone (and is in fact much drier than a bone, which is 20 per cent water), has enough water near its surface for NASA and others to be studying how it can be mined in order to extract oxygen and hydrogen fuel for future missions. Sampling undertaken by Wallace and Gromit during the Grand Day Out expedition of 1989 that indicated the presence of Wensleydale and other cheeses in the lunar regolith remains unexplained.

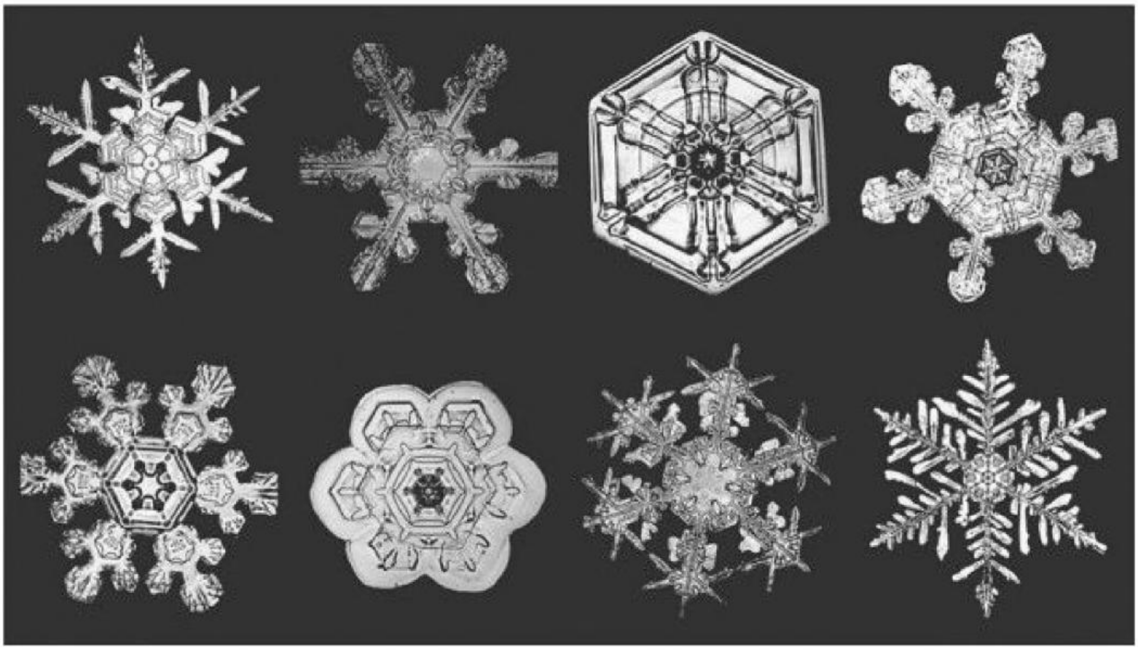
Carbon

If water is the ideal medium for life then, to a first approximation, carbon is life as we know it. A fundamental reason for this is that carbon is exceptionally versatile: uniquely, its atoms stick both to each other and to other elements – notably, hydrogen, oxygen, nitrogen and sulphur with up to four bonds at once. Water ice always configures into the same crystal structure, but at a wide range of temperatures carbon atoms can make long chains, or interlocked rings, or complex branching arrangements, or almost any other shape, and these can be foundations for molecules with very different properties. Around ten million configurations are known – from the crystals that make diamond, one of the hardest substances there is, to those of graphite, which is soft and almost greasy to the touch – and this is a small fraction of the carbon compounds that are theoretically possible. In living forms, carbon is the backbone of amino acids, proteins, carbohydrates and lipids. The versatility and transitions Debussy achieved in his music pale by comparison.

All the carbon on Earth was forged from lighter elements in stars billions of years ago. This has been known for several decades. But one of the most extraordinary discoveries of the last few years has been just how widespread in the cosmos are carbon-rich molecules that could act as building blocks for life. For example, more than twenty per cent of the carbon in space is thought to be associated with polycyclic aromatic hydrocarbons, or PAHs, which feature interlocking rings of six carbon atoms. PAHs are widespread in interstellar dust, and probably started forming shortly after the Big Bang. Areas of galaxies such as the Milky Way, meanwhile, are rich with ethyl formate, a carbon-based molecule that gives raspberries and rum their distinctive scents. In 2012 researchers showed that PAHs can be transformed in the conditions associated with new stars and exoplanets into even more complex precursors to amino acids and nucleotides – the raw materials of molecules essential to life such as proteins and DNA. Also in 2012 astronomers identified a sugar called glycoaldehyde in a binary star system about four hundred light years from Earth. Glycoaldehyde, a sugar molecule, is needed to form RNA, the likely precursor to DNA. In 2014 researchers reported the first discovery in the interstellar medium of a carbon-rich molecule with a branched structure. This finding, the researchers wrote, boded well for the presence in interstellar space of amino acids, for which a branched structure is a defining feature. And in 2015 NASA scientists announced that samples of pyrimidine, a ring-shaped molecule of carbon and nitrogen that is found in meteorites, are transformed by high-energy ultraviolet light into three of the key components of DNA.

The emergence of order

Life is more than a set of chemicals, however remarkable they may be. As the graphic on pages 90 and 91 shows, even the simplest living forms such as

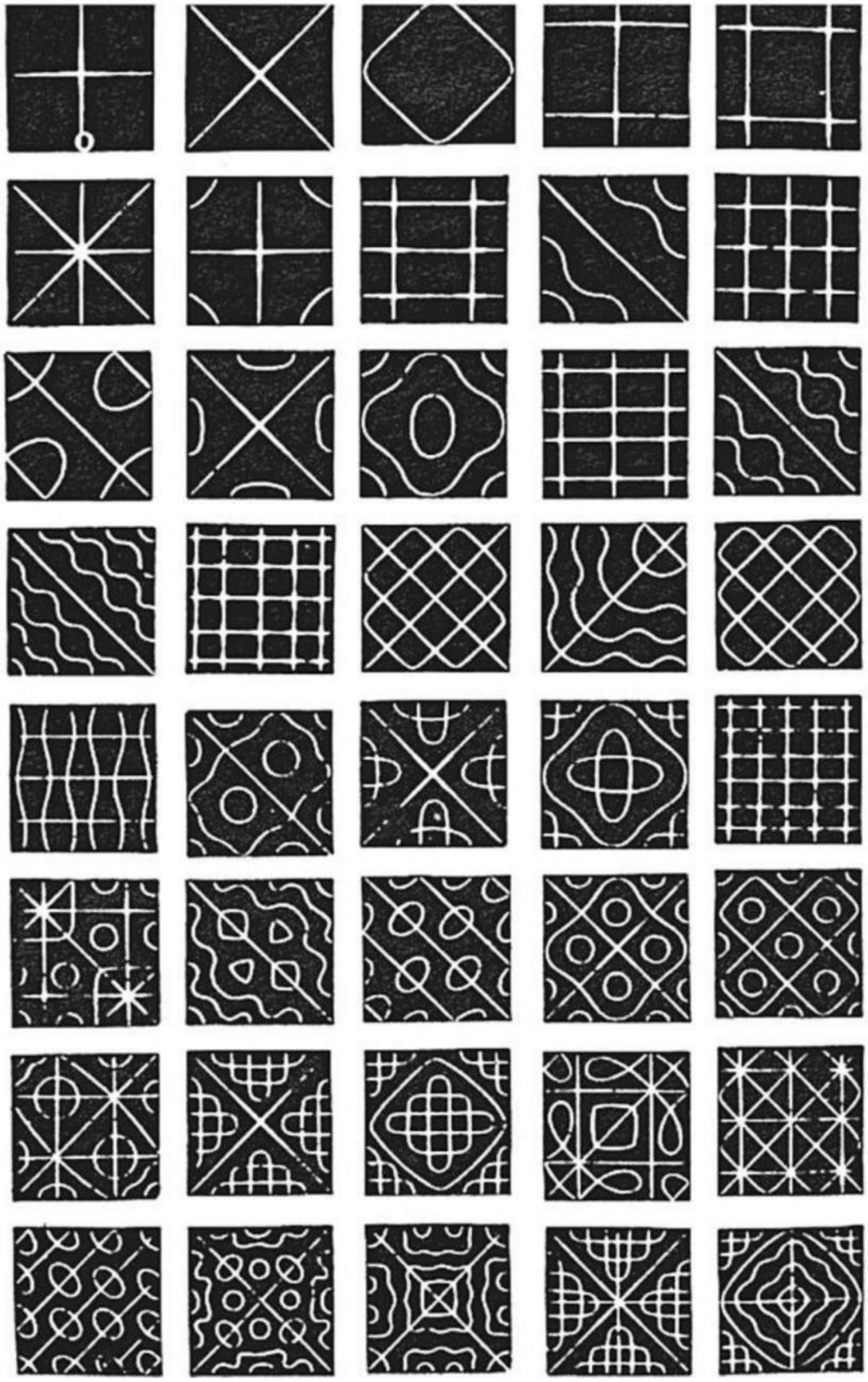


The hexagonal crystals of snowflakes are just one example of a self-created pattern in nature. Others include anfractuous, branch, brachia, cellular, concentra, contornare, crackle, filices, labyrinthine, lichen form, nebulous, phyllotaxy, polygonal, retiform, rivas, trigons, variegates, vascular and vermiculate.

Robert Hazen, a mineralogist and astrobiologist who researches life origins, notes that four things are necessary for simple and regular but often surprising patterns to emerge in non-living materials such as sand. First, there must be concentration: the individual particles must be present in sufficient numbers. Below a critical threshold, no patterns are seen. As particle concentrations increase, so too does complexity, but only up to a point. Second, there must be a flow of energy through the system: sand grains that may form lines on a beach or bar, for example, will not start moving without a certain minimum water-wave speed, though every complex patterned system also has a maximum limit to the energy flow it can tolerate. Third, complex patterns often tend to emerge when there is a cycling of energy flow such as freeze/thaw, wet/dry or day/night. And fourth, the particles need to be able to interact. Sand grains do this in very simple ways, such as by sticking or not sticking to each other, while the parts of more complex emergent systems have more ways of connecting and interacting with each other.

Barchan dunes in the Hellespontus region of Mars. Each is about sixty metres across.

But the number of ways in which the parts in an emergent system connect does not have to be very large, and the complexity with which they interact does not have to be very great, for remarkable things to happen. This is clearly shown in an artificial example: a computer program called the Game of Life. With five simple rules[22] governing the status of squares on a grid, the Game of Life generates dynamic patterns that behave in extraordinary ways – a magic trick that performs itself. 'Gliders' travel steadily across the screen. 'Eaters' consume any 'gliders' that pass. 'Breeders' grow bigger and bigger, replicating faster and faster. Patterns can even embody a universal Turing machine and a universal constructor, meaning that they can process information as well as any computer and build copies of themselves or any other pattern.



Sound waves create beautiful patterns in sand scattered on an even surface known as a Chladni plate.

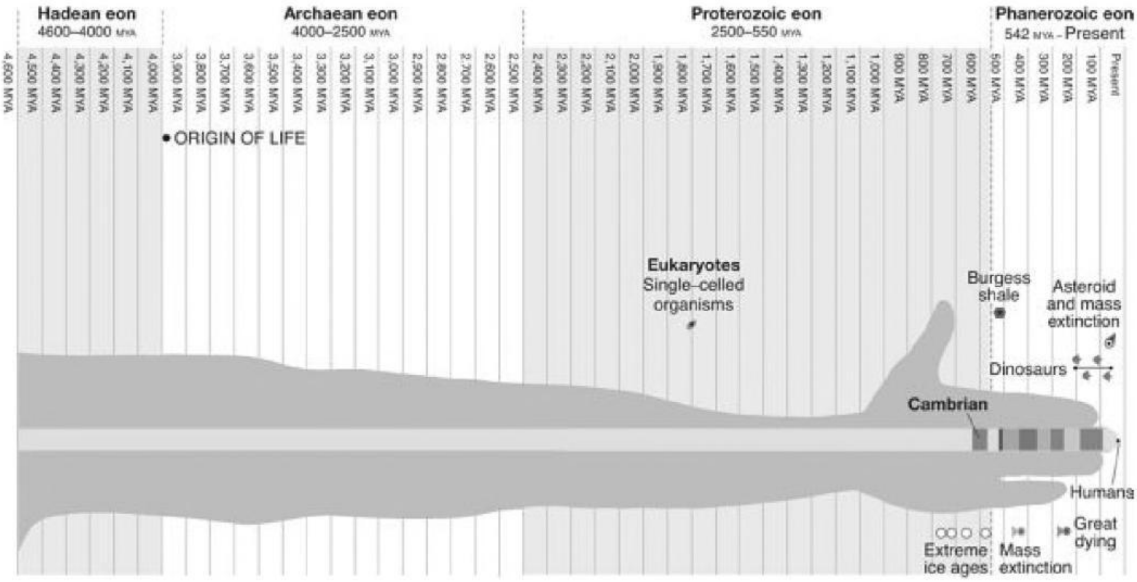
The Game of Life depends on an external agent to build the computer on which it runs (or on the board and stones of the game of Go, which is where it actually started). The agent must also write and run the rules or program. But if the material world around us is not governed by any external agent or programmer, the pieces have to come together and interact of their own accord.

For people educated in traditions which posit an external creator, the idea that nature can self-organize even to the extent of becoming living things can be troubling or implausible or both. By contrast, those educated in traditions in which pattern and process[23] are seen as inherent in things have less trouble with the idea. ('The great Tao flows everywhere,' wrote Lao Tzu. 'It loves and nourishes all things, but does not lord it over them.') Scientists, typically preferring the simplest possible explanation of any given phenomenon until proven wrong, favour a self-organized origin to life. Here are parts of some of the stories and hypotheses that scientists have developed over the last few decades to explore and test how life may have emerged on Earth.

First signs of life

Let's begin with the When? Until quite recently, it was widely thought that life on Earth began no earlier than about 3.5 billion years ago, some 500 million years into the Archaean eon, which succeeded the Hadean. In the last decade or so, however, evidence based on chemical signatures associated with life has suggested an earlier date – between about 3.8 billion and 4.2 billion years ago. If this earliest estimate proves to be correct then it would mean that life emerged – and perhaps re-emerged – quite quickly after events such as the Late Heavy Bombardment may have sterilized the planet's surface. And this raises the intriguing possibility that in the right circumstances the emergence of (simple) life is almost inevitable.

Every living thing on Earth shares the same chemistry, and can be traced back to a single Last Universal Common Ancestor, or LUCA, which is estimated to have lived between about 3.8 billion and 3.5 billion years ago. But LUCA was already quite a complex organism – something like a modern bacterium – and must therefore have evolved from simpler beginnings. Moreover, LUCA (or whatever it evolved from) may not have been alone. Rather than coming into existence just once, first life may have had many origins and many forms, emerging and evolving over and over again in different forms during millions of years, giving rise to the common ancestor of all we see today only when everything else was wiped out in the first mass extinction event.



The first eukaryotic cells evolved between about 2 billion and 1.6 billion years ago, but the first large and complex multicellular forms evolved less than 600 million years ago.

Second, the What? The answer to this question depends on what you mean by life. Among many definitions[24] I have read, the one credited to the researcher Gerald Joyce is as good as any: 'Life is a self-sustaining chemical system capable of incorporating novelty and undergoing Darwinian evolution.' But taking or leaving that definition, scientists agree that all the living things we know – and perhaps all those we can imagine describing as alive – share at least three[25] properties: a physical boundary between inside and outside; the capacity to store (and vary) information; and metabolism, or the ability to extract and use energy to maintain and grow.

Third, the How? The good news is that the scenarios currently under investigation are becoming increasingly comprehensive. Each contains much beauty and wonder. In addition, it is quite possible that experiments run over the next few years will lead to a robust and enduring explanation of the origin of life on Earth. To this it should be added that life can only exist as part of, and interacting with, larger systems.

Take the riddle of how living systems first acquired boundaries. Cells are mostly water on the inside, and most are surrounded by water on the outside. This makes sense because water is an excellent medium for transporting other molecules, but it poses a problem because water is also a very good solvent, liable to absorb and carry away the pieces needed for a complex system. It really wouldn't do to dissolve every time it rained. Life found a solution by creating cells surrounded by membranes made out of what are known as lipid bilayers, and all known cells have these membranes. Lipid bilayers have some imagined earlier in the chapter. Its onshore pools, exposed to an atmosphere very different from ours, would contain complex mixtures of dilute organic compounds from a variety of sources, including carbonaceous meteorites, and other compounds produced by chemical reactions associated with volcanoes and atmospheric reactions on Earth. Because of the fluctuating environment, these compounds would be undergoing continuous cycles in which they were dried and concentrated and then diluted upon rewetting. During the drying cycle, the dilute mixtures would form thin films on mineral surfaces. In these conditions compounds would react with one another and the products would be encapsulated in self-assembled membranes. In this way, vast numbers of what researchers call protocells – precursors of the first living cells – would have appeared all over early Earth.

Most of the protocells in this scenario would remain inert, but a few would contain a mixture that could be driven towards greater complexity by capturing energy, amino acids and nucleotides from outside. As these small molecules were transported into the protocell, energy would be used to link them into long chains (proteins and nucleic acids). Life began when one or a few of the protocells found a way not only to grow but also to incorporate a cycle involving catalytic functions and genetic information, presumably from RNA.

It sounds convincing, but there may be a catch. Some researchers argue that the energy accessible from sunlight and volcanic heat in conditions like this is insufficient to drive the emergence of, first, protocells, and then more complex forms. In a rival hypothesis, proposed by the chemist Michael Russell and championed by the evolutionary biochemist Nick Lane and others, life began at alkaline hydrothermal vents on the seafloor. These strange formations are quite different from the piping-hot 'black smokers' where yeti crabs and giant tubeworms live today. Rather than having a volcanic origin, alkaline vents are formed by a chemical reaction between seawater and rock newly exposed by the movement (at the speed of a growing toenail) of continental plates. The reaction produces methane and hydrogen-rich water, and expands and heats the rock, causing it to crack and fracture. This in turn permits more seawater to penetrate into the rock. At alkaline vent sites on Earth today, such as the 'Lost City' in the mid-Atlantic, the reaction extrudes twisted and precipitous limestone towers. The towers are filled with tiny cavities that happen to be about the size of bacterial cells, and methane and hydrogen bubble through and out of them into the water column above at between 40°C and 90°C. And, according to this scenario, it was in cavities like these that life began.

Russell, Lane and others claim that an alkaline vent origin is the only hypothesis that solves the question of metabolism:[28] the puzzle of how proto-life was able to capture enough energy to assemble and evolve. Raw hydrogen bubbling from the ground as gas, as it does at an alkaline vent, is 'a free lunch you are paid to eat'. The temperature and acidity differences across the tower walls create a weak but vast battery. The vents are therefore an environment that favours the emergence of greater complexity because they provide a steady stream of free energy that is essential for the energy-hungry reactions needed to make complex polymers such as proteins, lipids, RNA and DNA. And, exploiting the electron and proton gradients across these vent walls, the Last Universal Common Ancestor of everything on Earth alive today set the pattern for all future organisms, which recapitulate across their cell walls the chemistry of oxidation and reduction found in warm alkaline vents today. If this is right, then all of us carry within a memory of an ancient 'Lost City' on the ocean floor.

Back in the seventeenth century Athanasius Kircher envisaged water and fire coursing through the inward parts of the Earth, driving turbulence and change.[29] We now know this to be a distorted but not entirely misguided intuition of reality. We have known since the mid-twentieth century that heat from the planet's core drives tectonics: the movement of continental plates across its surface, cycling and recycling rock and water over billions of years. Thermal activity at alkaline vents and hot smokers are small parts of these much larger loops. But since then an even more astonishing reality has become apparent.

Life – Earth scientists now generally agree – moderates the planetary system to its advantage. Its influence extends as far as the upper atmosphere, where it has created the ozone layer that blocks high-energy ultraviolet rays and so allowed the spread of plants and everything that depends on them across the continents. Over billions of years, life has altered not just the skin and sky but also the Earth's deep subterranean realms, pulling carbon from the mantle and piling it on the surface in the form of sedimentary rock, and sequestering huge amounts of nitrogen from the air into ammonia stored inside the crystals of mantle rocks. By controlling the chemical state of the atmosphere, life has also altered the rocks it comes into contact with, and so oxygenated the crust and mantle of Earth. This changes the material properties of the rocks – how they bend and break, squish, fold and melt under various forces and conditions. The clay minerals produced by Earth's biosphere soften Earth's crust and have helped to lubricate the plate tectonic system that would otherwise have ground to a halt. Life is not a minor afterthought on an already functioning Earth, but has become a central part of its nature and process.

Stupendous contrivances: wonders of the cell

For the initial 1.7 billion or so years of its existence, life consisted solely of microbes – the precursors of today's bacteria and archaea.[30] Innovations made early on by these relatively simple creatures still power every cell in our bodies and those of everything else that lives. But it is only very recently that we have begun to see and fully appreciate their reality.

The first glimpses of a tiny invisible world came in the seventeenth century. In the 1670s the microscopist Antonie van Leeuwenhoek used tiny lenses – drops or globules of glass – that magnified by anything from about 275 to 500 times to observe 'animacules' present in countless numbers in even the most innocuous body of water (as well as in places less innocuous, such as saliva from the mouths of old men who had never brushed their teeth). These animacules we now know as protists – broadly, pond life – and bacteria. Van Leeuwenhoek's contemporary Robert Hooke had inferior microscopes but superior powers of communication, at least in English, and in his *Micrographia* of 1665 he published images of marvels never before imagined: tiny 'cells' in cork (named for their supposed resemblance to the cells in which monks lived in a monastery); the eyes of a fly revealed by magnification as monstrous compounds; and the alien body-armour and mouth parts of a flea. 'Nature', wrote Hooke, 'not only work[s] mechanically, but by such excellent and ... stupendous contrivances, that it were impossible for all the reason in the world to find out any [more ingenious].'

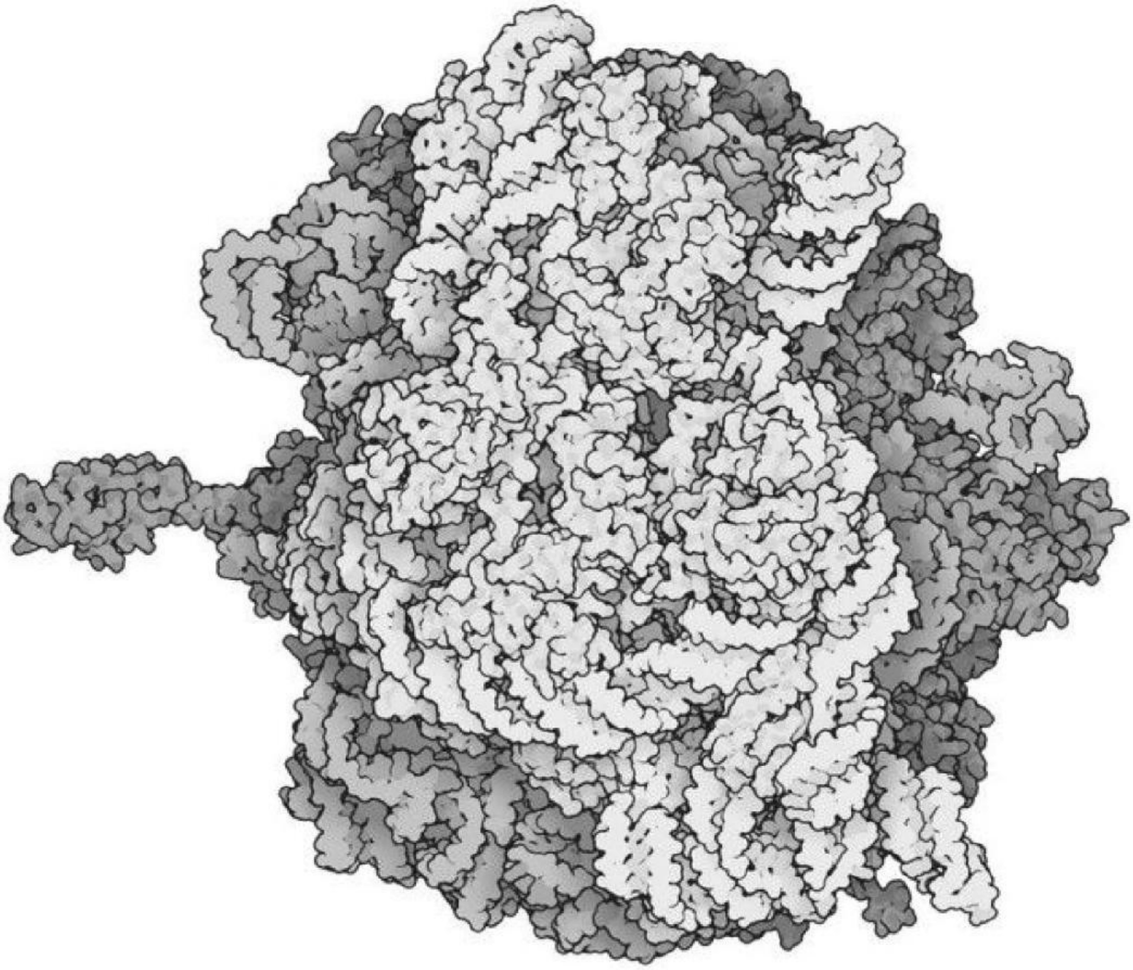
In recent decades researchers have found that the mechanical workings of nature operate at a much, much smaller scale than anything contemplated by van Leeuwenhoek or Hooke. For at the nanoscale (where measurements are made in nanometres – billionths of a metre), life is made of molecular machines. And 'machines' here is not a figure of speech: these entities are assemblages of moveable parts that rearrange other molecules in ways as regular as clockwork. These machines differ from those we are more familiar with, however, in being capable of continuous self-assembly, repair and disassembly, and in being much more reliable than anything humans have made, having endured essentially unchanged for billions of years. They are, I think, truly stupendous: as great a wonder for our generation as anything discovered by van Leeuwenhoek and Hooke was for theirs. Here are two examples.

The first is the ribosome: a tiny 'factory' that makes all the proteins essential for life. (There are about twenty-five thousand different kinds of protein in a human body. Most individual protein molecules last only a few days so they need to be steadily replaced.) Ribosomes are so fundamental that it is hard to see how cells as we know them could ever have come to be without them. They are found in every cell of everything alive, and have the same essential structure in all of them. Their active sites and central cores are built of entirely of RNA, so ribosomes could be evolved relics or adaptations from an RNA world. At the base of everything that is your material presence in the world are their numberless goings-on, inaudible as dreams.

Compared with molecules such as water and simple sugars, ribosomes are enormous, consisting of about a million atoms; but compared with cells they are tiny, and a typical human cell can contain many millions of them. Each ribosome, which consists of large and small subunits like parts of a robotic press, reads information conveyed to it from DNA in the cell nucleus by messenger RNA rather as if it were reading brail, and uses the information to select and then stamp together amino acids so that they form new proteins. It does this at the rate of about forty per second, and with an error rate of less than one in ten thousand – far better than humans achieve in high-quality manufacturing. All in a space just twenty to thirty nanometres across.

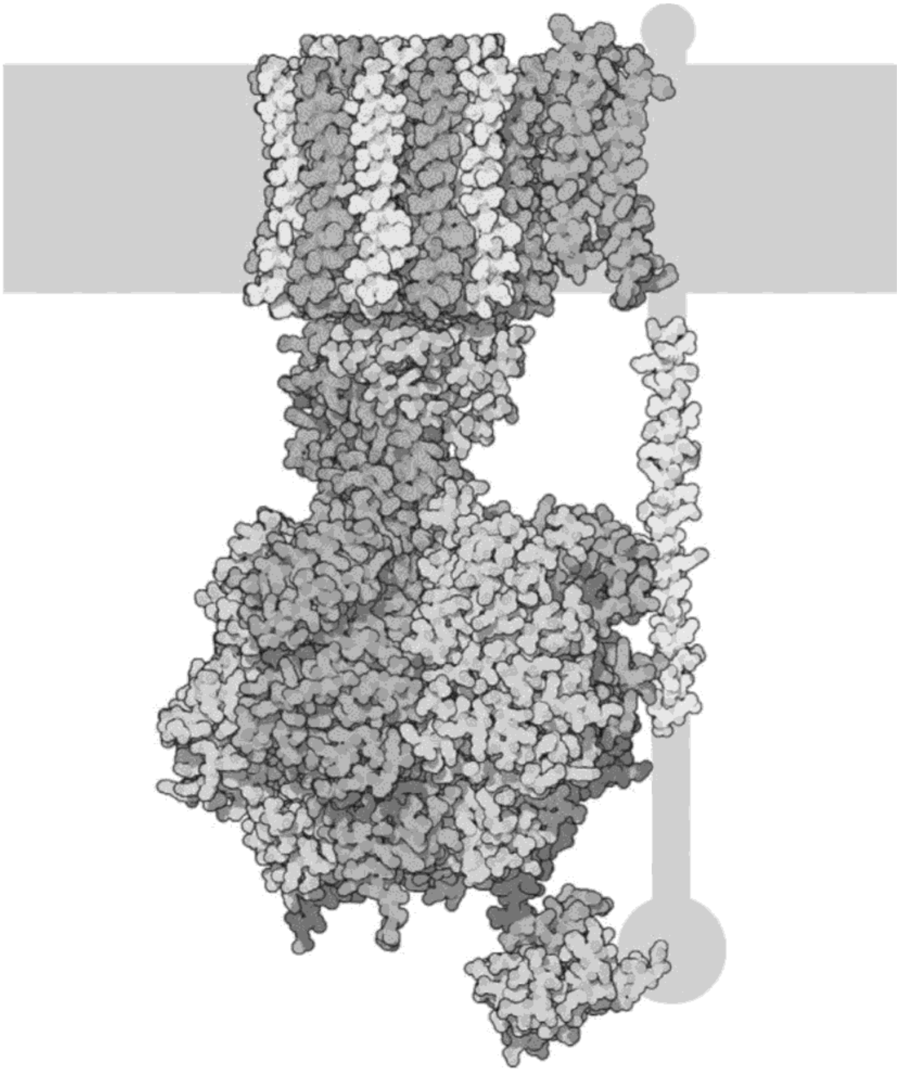
The physicist Neil Gershenfeld calls ribosomes the original digital fabricators, 4 billion years ahead of 3D printers, and vastly more capable and reliable. With a 3D printer, the design is determined by a computer program, which is digital, but the material with which it works, such as a resin, has no self-organizing properties: it is just kind of smooshy. In the case of a ribosome, however, the twenty amino acids it 'prints' with come in regular and repeating shapes – a fair analogy is Lego bricks – and this makes fabrication repeatable and precise even as a very large number of configurations is possible. To an extent, the 'code' is also in the material, because the shape of the parts directs them to configure in a limited number of ways.

There's an old joke about two men taking a break outside on a cold day. One pours hot tea from a thermos into two cups. 'You know,' he says, 'this flask is incredible. In winter it keeps the tea hot, but in summer, when I fill it with iced tea, it keeps it cold. The question I ask myself is, how does it know?'



The ribosome manufactures all the proteins essential to life in every living thing, and likely predates life as we know it.

The answer to the question of how many molecules inside a cell 'know' where to go is a little like this: they don't. The fluid within a cell, which is called the cytoplasm, is mostly water, and in a simple cell bacterium many molecules and large assemblies of molecules float freely within it. At any temperature above absolute zero, all molecules vibrate. That is what heat is. At room temperature, a medium-sized protein floating in the watery medium of a cell and jiggled by random motion moves at about five metres per second – the speed of a fastish runner. If placed alone in space, the protein will travel its own length in about a nanosecond (a billionth of a second), but inside the cell, battered from all sides by water molecules, it will take a thousand times longer (a millionth of a second) to move that same distance. Cells are, however, tiny. A bacterium such as *E. coli*, for example, is about seven-thousandths of a millimetre long and less than two-thousandths of a millimetre wide. And because of this, random motion[31] is fast enough to transport many amino acids and proteins inside to where they are needed simply by bumping around until they find the right place. Any molecule in a



ATP synthase: precision nano-engineering of the highest order. 'The more we learn about it,' says the biologist Nick Lane, 'the more marvellous it becomes.'

Tucked away in the offices of the Mitochondrial Biology Unit in Cambridge is a scale model of ATP synthase made, as it happens, out of Lego bricks. Over a metre high and enormously detailed, it is, in a sense, just a gimmick – something to help children and ignorant adults like me get a superficial sense of one of life's most astonishing machines. All the same, it blew me away when I first saw it, and I stood almost speechless as the man who, perhaps more than any other, helped to elucidate the structure of this extraordinary molecular machine showed it to me. John Walker, who won a Nobel Prize for his work, was generous to a fault with his time and, despite the Nobel accolade, direct and humble. He remains someone for whom the work and the wonder matter above all. 'Working this thing out,' he told me quietly, 'was quite an effort.'

Life itself

In the introduction to this book I described a patch of sunlight on a kitchen ceiling. The light had passed between the branches of a tree which was moving in the breeze and casting ripples on the patch of light. The tree and the human perceiving the dappling shadows cast by the tree have a common origin. They have their differences. The tree, for example, 'eats' light, performing amazing tricks such as exploiting quantum effects to maximize the efficiency with which it does so. But both tree and human share the same biochemistry and many of the same essential mechanisms working away without cease, including the ribosome and ATP synthase.

Two or three years ago a friend invited me to join him on a descent of a small river in mid-Wales. The Llyfnant, he said, was just about the only truly wild river left in that excellent country, and we would be going offtrack into one of the last remaining fragments of Atlantic rainforest in Britain. Few people ventured there. Some days later, as we walked beside the river on a tarmac road behind a local council rubbish truck with a Keep Wales Tidy sticker on the bumper, I wondered where it had all gone wrong. But gradually the shape and feel of the valley began to change. The lorry pulled ahead, leaving only the sound of the river and the wind in the trees. As we walked, the river fell away from the road into a gorge, and the understory of the woods between us and the river became increasingly dense and luxuriant. Liverworts, lichens and epiphytic ferns spread across rock faces and the nooks and branches of trees. My friend observed with joy that the trees soaring above us were not oaks but small-leaved limes, *Tilia cordata*. These, he explained, were trees of the ancient woodland – evidence that the place had flourished undisturbed for hundreds of years and even since prehistoric times.

We cut down the slope, slipping and falling but landing on soft moss and thick soil until, with a bit of clambering, we reached the river at a point where it poured between large rocks over a stone lip and down a steep channel into a pool four or five metres below. Here we sat down, ate our sandwiches, and stared into the water. Then, without warning, a salmon jumped from the pool at the base of the fall, thrusting upwards as if it were trying to get some purchase on the air itself before it fell back in the downward rush of the thick pipe of falling water. It tried and failed repeatedly, and when it did finally succeed in jumping to the upper pool I found myself cheering. I was, I realized, completely happy and at home in this place. That night, as on many nights since, I dreamed of the wildwood. It is a real place but also an inscape, a vibrancy in the soul.

The sun came out and I looked at the ring on my finger. A familiar fact came to mind but more as a feeling than as an idea: all the matter in and around me, including the gold in that ring, *really was* formed billions of years ago in stars and supernovas – and, if we are wise and generous enough, will continue to play at being endless forms most beautiful long after I am gone.

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1 'I have scarcely touched the clay, and I am made of it.' Antonio Porchia

2 Most of the atoms in our bodies – about 62 per cent – are hydrogen, but because they are so much smaller than other atoms they are only about 10 per cent of our mass. About 24 per cent of our atoms are oxygen but they are 65 per cent of our mass. Carbon atoms are 12 per cent of all the atoms in our bodies and 18 per cent of our mass.

3 The smallness of the proportions of some elements does not mean they are insignificant. We are only 0.0042 per cent iron, for example, but without it we would die immediately.

4 The Big Bang might actually have been a Big Bounce. 'Our universe,' says the physicist Carlo Rovelli, 'could be the result of a previous contracting universe passing across a quantum phase, where space and time dissolved into probabilities.'

5 The cosmic microwave background is detectable as very slight differences in temperature across the entirety of deep space. It is the oldest light in the universe: an echo, and a map, of the distribution of matter and energy about 380,000 years after the Big Bang. It presents a cosmological analogue for something the psychologist William James said about thunder: 'The feeling of the thunder is also a feeling of the silence as just gone.'

6 The oldest known stars, such as HD 140283 (which is nicknamed the Methuselah Star) and SM0313, are about 13.6 billion years old.

7 The Earth rocks: thunder, echoing from the depth, roars in answer; fiery lightnings twist and flash ... Sky and sea rage indistinguishably.' Aeschylus, *Prometheus Bound*

8 Ever since it was sheared off from the Earth, the Moon has been gradually getting farther away as it endlessly circles us. At present it is about 384,400km away, and retreating at 3.8 centimetres a year, meaning it has retreated nearly 2 metres since the Apollo landings. If the Moon suddenly disappeared, a lot of the water it currently attracts towards the Earth's equator would be redistributed to the polar regions and the Earth's rotation would become much more erratic, with drastic impacts on regional climates.

9 The starting temperature at the World Sauna Championships in Finland in 2010, the year before it was abolished, was 110°C. Half a litre of water was poured on the stove every thirty seconds. The winner was the last person to stay in the sauna and walk out without outside help. Alcohol consumption was prohibited prior to and during the competition.

10 'notice ... how the little animal wins its way up against the stream, by alternate pulses of active and passive motion, now resisting the current and now yielding

to it in order to gather further strength and a momentary fulcrum for a further propulsion.’

11 Nonpolar volatile molecules, like methane on Titan and carbon dioxide on Venus, can’t form droplets, so ‘rain’ does not exist there, just a constant, dreary mist ... like England in February but with more charm.

12 ‘Wind and sea. Everything else is provisional. A wing’s beat and it’s gone.’ Kathleen Jamie

13 In 2015 the Cassini spacecraft flew through the water plumes of Enceladus and found them to be rich in molecular hydrogen – evidence that the Moon’s underlying sea could support microbial life.

14 The only known body in the solar system besides Earth with large amounts of liquid on its surface is Titan, Saturn’s largest moon. But the liquid of its lakes and seas is methane, ethane and propane, oozing at a balmy –179ºC and possibly erupting every now and then with dramatic patches of bubbles.

15 Though some arrived in comets and asteroids, water was probably present in and on the material from which the Earth formed, gradually escaping to the surface through volcanoes on the new planet. But a part of the water around us may also be a matter of continuous creation. Deep within the mantle, at 20,000 times atmospheric pressure and temperatures of around 1,400°C, silicon dioxide is thought to react with liquid hydrogen to form silicon hydride and liquid water that is then released in earthquakes.

16 The Moskenstraumen, a system of eddies and whirlpools in the Lofoten archipelago off the Norwegian coast, appears on Olaus Magnus’s Carta Marina of 1539 and in Edgar Allan Poe’s 1841 story ‘A Descent into the Maelström’. It is one of the strongest such systems in the world, but nothing like as strong as Poe imagined. Nor does it drain the sea as Kircher supposed.

17 A diamond that was spat out of a volcano in Brazil 90 million years ago appears to have been created in the presence of water as far as 1,000 kilometres down.

18 Three thousand kilometres beneath the Earth’s surface is the core: a sea of liquid metal surrounding a super dense ball of solid iron and nickel a little smaller than the Moon, and bristling with a forest of iron crystals up to one hundred kilometres long.

19 ‘The self-assembly process seems to defy our intuitive expectation from the laws of physics that everything on average becomes more disordered.’ David Deamer

20 Some researchers say it may one day be possible to characterize emergence as a physical law. Robert Hazen suggests it may be something along the lines of $C \geq \Sigma [n, i, \Delta E (t)]$. At any rate, emergence happens, and it has what the physicist Frank Wilczek calls the beautiful exuberance and productivity of a physical law.

21 Ice crystals are hexagonal because individual molecules are shaped like tetrahedrons. As water freezes, these tetrahedrons come closer together and crystallize into a hexagonal structure.

22 Cells on the grid are either alive (on) or dead (off). A live cell with zero neighbours or one live neighbour dies; a live cell with two or three live neighbours remains alive; a live cell with four or more live neighbours dies; a dead cell with three live neighbours comes alive; and in all other cases a dead cell stays dead.

23 ‘The study of non-equilibrium thermodynamics seems to be telling us that … the appearance of life on a planet like the early Earth, imbued with energy sources such as sunlight and volcanic activity that keep things churning out of equilibrium, starts to seem not an extremely unlikely event … but virtually inevitable.’ Philip Ball

24 At the reductive end we have the Nobel Prize-winning physiologist Albert Szent-Györgyi: ‘Life is nothing but an electron looking for a place to rest’, and the geologist and chemist Michael Russell: ‘The “purpose” of life is to hydrogenate carbon dioxide.’ The physicist Sean Carroll observes: ‘Every organism … acts to increase the entropy of the universe.’ *Kurzgesagt*, a popular video series, suggests that life is ‘an openness to creating new patterns’.

25 At the risk of sounding like the Spanish Inquisition, some accounts list six essential properties shared by all life on Earth:

(1) compartmentalization – a cell-like structure that separates the inside from the outside;
(2) hereditary material – RNA, DNA or equivalent to specify form and function;
(3) catalysts to speed up and channel these
(4) metabolic reactions; a supply of free energy to drive metabolic biochemistry – the formation of new proteins, DNA, etc.;
(5) a continuous supply of reactive carbon for synthesizing new organics;
(6) excretion of waste.

26 The biochemist Pier Luigi Luisi and his colleagues have shown that lipid vesicles can grow, gradually incorporating new lipid molecules from solution, and that they are autocatalytic – that is, they can act as templates that trigger the formation of more vesicles and, in a kind of self-replication, divide. Luisi has proposed a ‘Lipid World’ scenario for life’s origin, in which prebiotic lipids formed abundantly on Earth and self-organized into cell-like vesicles that captured an early information-bearing molecule.

27 Some viruses today still use RNA for heredity. They may provide clues to what an ‘RNA world’ was like.

28 Recent research supports the hypothesis that chemical reactions occurring spontaneously in Earth’s early chemical environments provided the foundations upon which life evolved – in other words, that metabolism is older than life itself. Markus Ralser and others have discovered that a version of the cirtic acid cycle (a series of chemical reactions used by all aerobic organisms to generate energy) can proceed in the absence of cellular proteins called enzymes.

29 ‘The fire and water sweetly conspire together in mutual service.’

30 After the best part of 2 billion years of only microbial life on Earth, an archaeon engulfed a bacterium without digesting it and gave rise to larger, more complex cells called eukaryotes, which are the ancestors of plants, animals and fungi.

31 Molecules in the air around us jiggle much faster than they do in water at the same temperature. If we shrank to the size of molecule, says the physicist Peter Hoffman, we would be bombarded by a molecular storm so fierce it would make a

We hear first. Five months after conception, when a human foetus is typically about half the size it will be at full term, its eardrums and the inner bones of the ear are already near adult size. Its acoustic nerves are mature and can conduct signals, and the temporal lobes of the brain, which process sound, are also functioning. The foetus can hear low sounds, and one of the first it hears is the swell of its mother's blood as it is pumped through her aorta with every beat of her heart. By six to seven months a foetus can hear pretty much the full range of its mother's voice,[1] though in a muffled sort of way. Certain tones and patterns, spoken or sung, may prompt it to move or stay still, and sometimes the mother and baby start 'talking' to each other – the foetus moving to certain sounds, especially song, and the mother sensing this and repeating those sounds.

Thanks to ultrasound, a tiny heartbeat from within the womb is the first sound made by their baby that many parents hear. The first time I heard it as a father-to-be I found its speed, at well over a hundred beats per minute, both thrilling and terrifying. Seeing my anxiety, the nurse gently explained that the rate was perfectly normal for the baby's stage of development. I calmed down a little but continued to listen in awe.

Seen in the context of the spectrum of heart rates across the entire animal kingdom, a human baby's heartbeat is neither very fast nor very slow. Hummingbird hearts can beat well over a thousand times per minute. The heart of a clam beats twice a minute when it is a calm clam, rising to twenty times per minute at party time. Nevertheless, the rapid beat of the heart of a foetus, a baby or a young child – the rhythm of a life just beginning – remains one of the most sublime things I know: beautiful but also disturbing in its relentlessness.

In situations of stress, joy or arousal, we are quite often aware – or imagine that we are aware – of the heart beating within us. We don't perceive any other organ in this way: the wrenching or turning of the guts is quite different. This contributes to a sense that the heart is at the centre of some of the things that matter most in our being. Clearly, this goes a long way back. In ancient Egypt the heart, *Ib*, was believed to be the most important manifestation of the soul, and surpassing happiness was *Awt-ib*: 'wideness of heart'. The heart was the only major organ left in a mummy after death so that it might be weighed against a feather of Maat, the goddess of truth, harmony and justice, to judge how well a person had lived. Still today in various traditions the heart is seen as central to what is most precious in us. In Laghunyasa, a meditation in the Hindu tradition, Shiva – the Supreme

Being who creates, protects and transforms the universe – is visualized as residing in the heart. In the whirling meditation of Sufis, dervishes revolve from right to left around the beat of the heart in order to express an embrace of all humanity. And in the European Romantic tradition, many feel strongly the truth of John Keats's declaration, 'I am certain of nothing but the holiness of the heart's affections and the truth of the imagination.' Recent scientific research suggests that people who are aware of their own heartbeat are better at perceiving the emotions of others.

Attempts to retain a sense of decency in dark times have been mindful of these resonances. In the 1960s, fearing that distance and abstract language could blind the US President to the enormity of a nuclear strike, the lawyer Roger Fisher suggested that, instead of having the launch codes in an attaché case carried by a young officer constantly at the President's side, the codes be surgically implanted in a capsule beneath the officer's heart. Then, if the President decided that the murder of tens of millions of people was necessary, he would himself have to access the codes by using a butcher's knife to gouge out the young man's heart. Fisher reported that when he put this proposal to friends in the Pentagon high command, they said, 'My God, that's terrible ... [The President] might never push the button.' But the heart can also be recruited and enchained in systems of insidious control and oppression. In Dave Eggers's 2013 satirical novel *The Circle*, the protagonist Mae Holland wears a 'SeeChange' camera – part of the new universal surveillance system – in a lovely pendant that sits on her breastbone directly in front of her heart. In real life, sociometric badges, which hang around employees' necks in this fashion and monitor their every move and interaction, are already being piloted by several companies.

The discovery of the heart

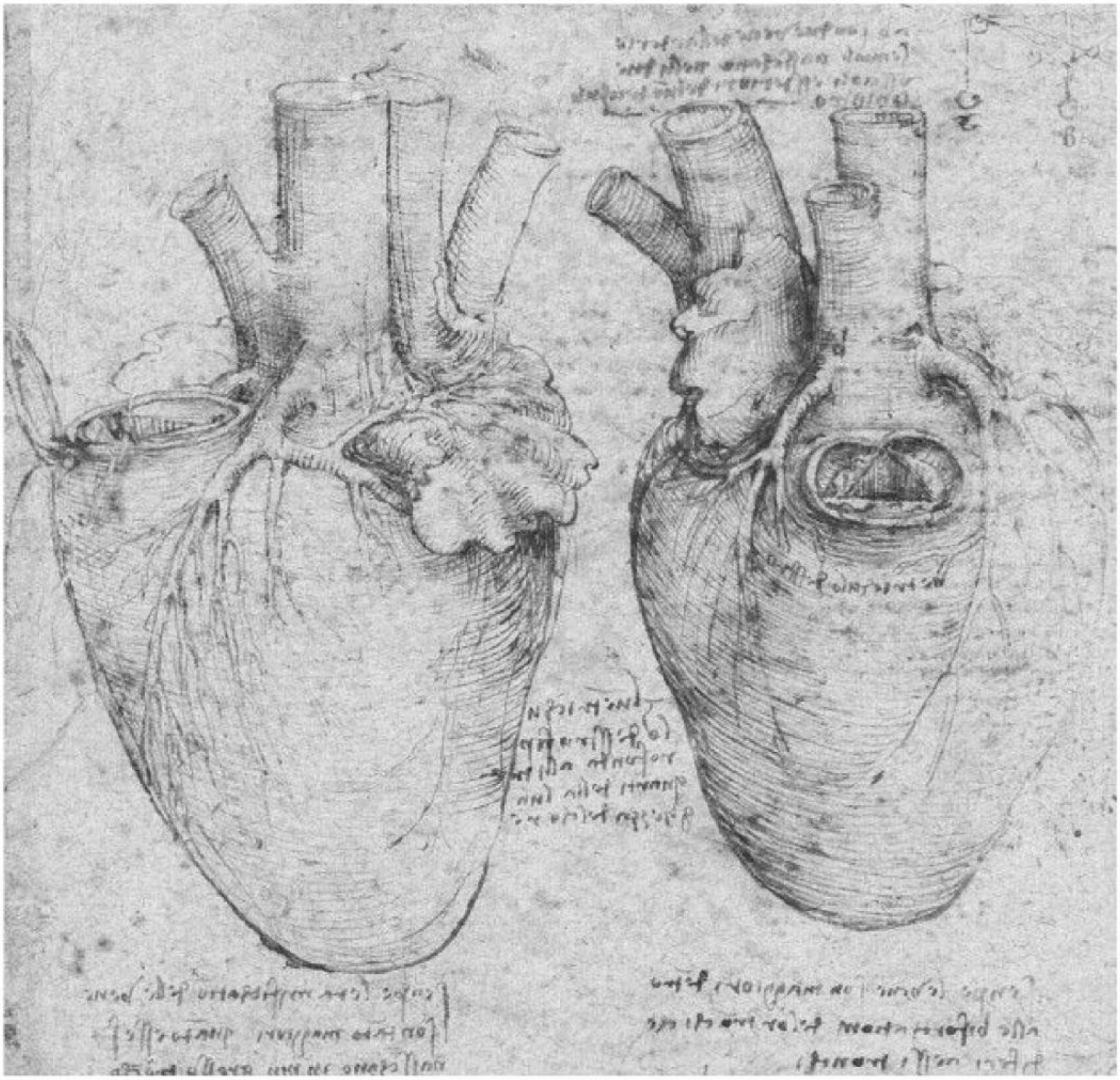
For most of human history people have had little idea what the heart is for or how it works. This may seem odd to those of us educated in modern industrial societies, but there is nothing intuitive in the idea that the main purpose of the heart is to pump blood around the body. The circulation of the blood is no more obvious to the naked eye than is the fact that the Earth orbits the Sun. Arteries and veins appear to peter out in the tissues of the body, and the capillaries that we now know join them to complete the circuit through which our blood travels are so fine that they are invisible without a microscope.

The Roman physician Galen, who flourished in the second century AD and whose ideas dominated European medicine for more than fifteen hundred years, was impressed by the size and central position of the liver in the human frame, and he placed this organ rather than the heart at the centre of the life of the body. He taught that blood is one of four humours, the other three being yellow bile, black bile and phlegm. Supposedly, food digested in the gut passed through the portal vein into the liver, where it was transformed into blood and imbued with what Galen called 'natural spirits'. The great veins then carried this brew sluggishly to the tissues of the body, which consumed the spirits before returning it for fresh nourishment along those same veins. Meanwhile, according to Galen, some blood from the liver travelled into the right side of the heart, where it met air from the lungs. The encounter produced a kind of fire, and hence the warmth so characteristic of a living body. But the blood was not consumed by this fire; rather it was refined and, passing somehow through the septum (the dividing wall in the middle of the heart) to the chambers of the left side, produced 'vital sprits' that then flowed through the arteries to quicken movement in the body and thought in the brain.

Galen's understanding of the heart was wildly wrong and has long since been rejected by medical science. But his doctrine of the four humours has – in its corollary of the four temperaments[2] – had a remarkable afterlife. It lurks behind typologies such as the Myers–Briggs Type Indicator, which supposedly distinguishes different personality types and was quite widely used until at least the late twentieth century. It even endures in the minds of scientists in an imagined future. In Kim Stanley Robinson's 1993 science fiction novel *Red Mars*, a chronicle of twenty-first-century planetary settlement, the psychologist Michel Deval finds to his surprise that it offers a good lens for analysing the different personalities of the first colonists. Perhaps the enduring appeal of Galen's doctrine is that it seems to readily unlock the mystery of corporeal being, and do away with doubts and uncertainties – something that is especially welcome in the face of illness or anxiety. By contrast, modern medicine at its best accepts complexity and uncertainty. The human body, says the physician Atul Gawande, can be 'scarily intricate, unfathomable, hard to read', and this recognition is sometimes less comforting than false hope.

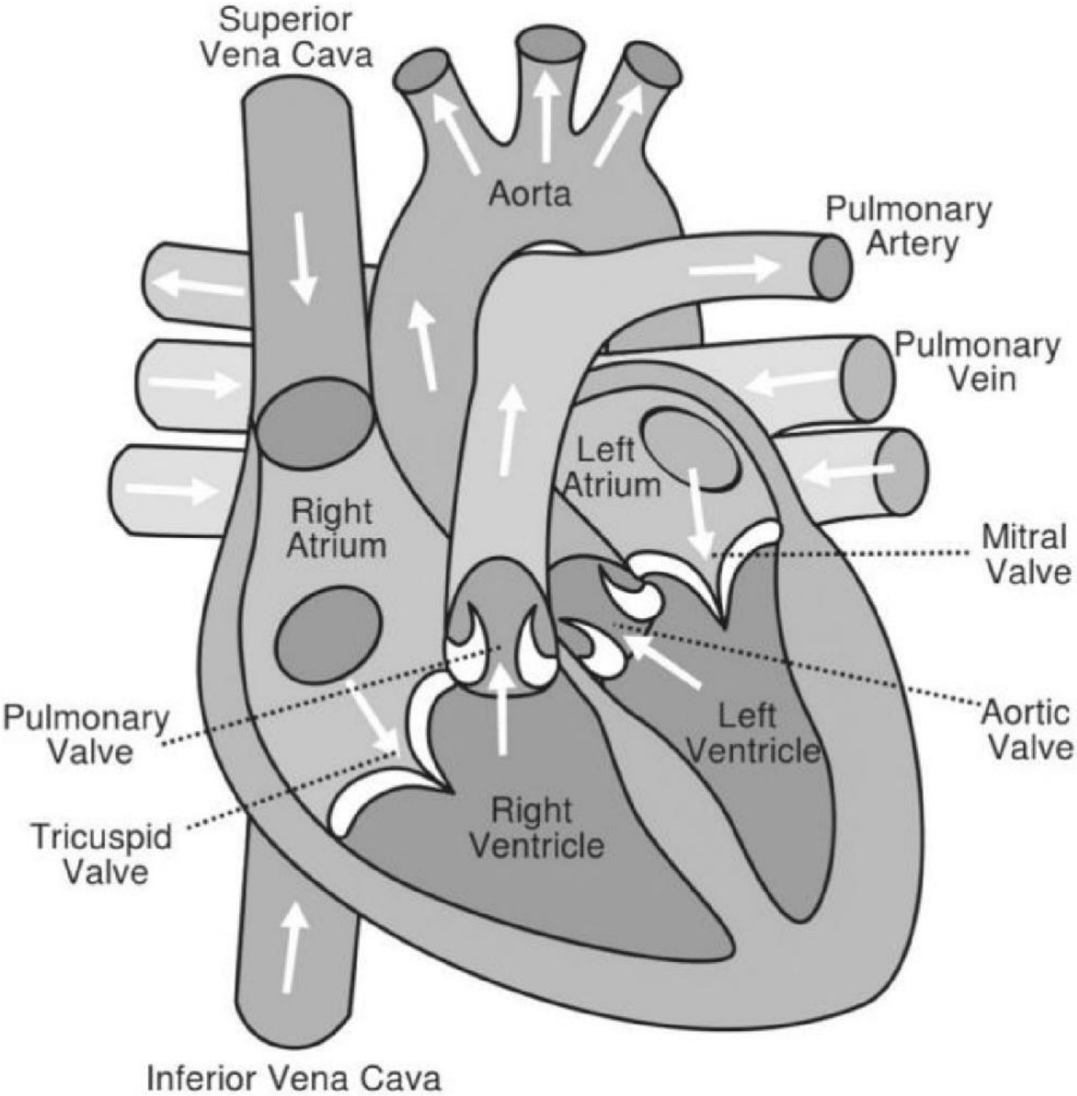
Some of the biggest steps towards a modern understanding the heart were taken by Leonardo da Vinci in the early years of the sixteenth century. Indeed, he began to understand the heart in ways that were unsurpassed in some respects until the late twentieth century. From around 1508 to 1513, six years before he died, Leonardo undertook detailed study of the inner anatomy of the human body – the skeleton, muscles, tendons and nerves, the reproductive system and the major organs, notably the heart. A military engineer[3] as well as a supremely skilled artist, he applied his understanding of levers and fluid flow and of the subtle movements of living beings to his investigations. He produced anatomical drawings that have seldom if ever been surpassed for detail or accuracy, let alone beauty. Perhaps, after decades attempting to capture the sublime in outward appearance in his paintings, he was now searching for beauty that, in the writer Ursula Le Guin's phrase, is not just skin-deep but life-deep.

Working for the most part with the hearts of oxen and pigs, and only later with those of humans, Leonardo realized that the heart is first and foremost a muscle. He saw that it had four chambers where Galen had said there were two, and that the upper two – the atria – contract at the same time, followed by a simultaneous contraction of the lower two, the ventricles. He saw that the pulse in the wrist keeps time with the beat of the heart, and he attempted to calculate cardiac output (the amount of blood that leaves the heart each minute). He appreciated that the valves were one-way structures – something that was incompatible with the Galenic belief in the continuous flux and reflux of the blood. He also worked out that turbulent movement in the blood helps the heart valves to open and close – a fact that was again fully understood only in the late twentieth century. He discovered and drew bronchial arteries and also described the moderator band, rightly identifying it as a muscular bridge between the walls of the right ventricle that prevents overdistention. His insights were so many and so deep that it is hard to believe he did not realize that the heart pumps blood around the body. There is, however, no clear statement to this effect in his surviving notes. In any case, Leonardo never published his work on the heart, and it was unknown to his contemporaries and all but forgotten until nearly five hundred years later, when his sketches and notes were finally examined by expert eyes. As a result, his successors had to grope their way without the benefit of his discoveries.



In *On the Fabric of the Human Body*, published in 1543, the anatomist Andreas Vesalius brought the standards of fine art and the rapidly advancing field of evidence-based cartography to his new maps of the inner world. Vesalius, who became professor of anatomy at Padua University, took great pains in his observations of the corpses he dissected and he was able to correct many of Galen's errors, such as the idea that the great blood vessels originate in the liver. Vesalius also questioned the doctrine that blood passed through unseen pores in the septum of the heart. But he couldn't entirely shake off the weight of tradition, and held to the Galenic idea that different types of blood flow through veins and arteries. Nevertheless, Vesalius's scepticism and his confidence in first-hand observations encouraged others to continue to question Galen's authority.

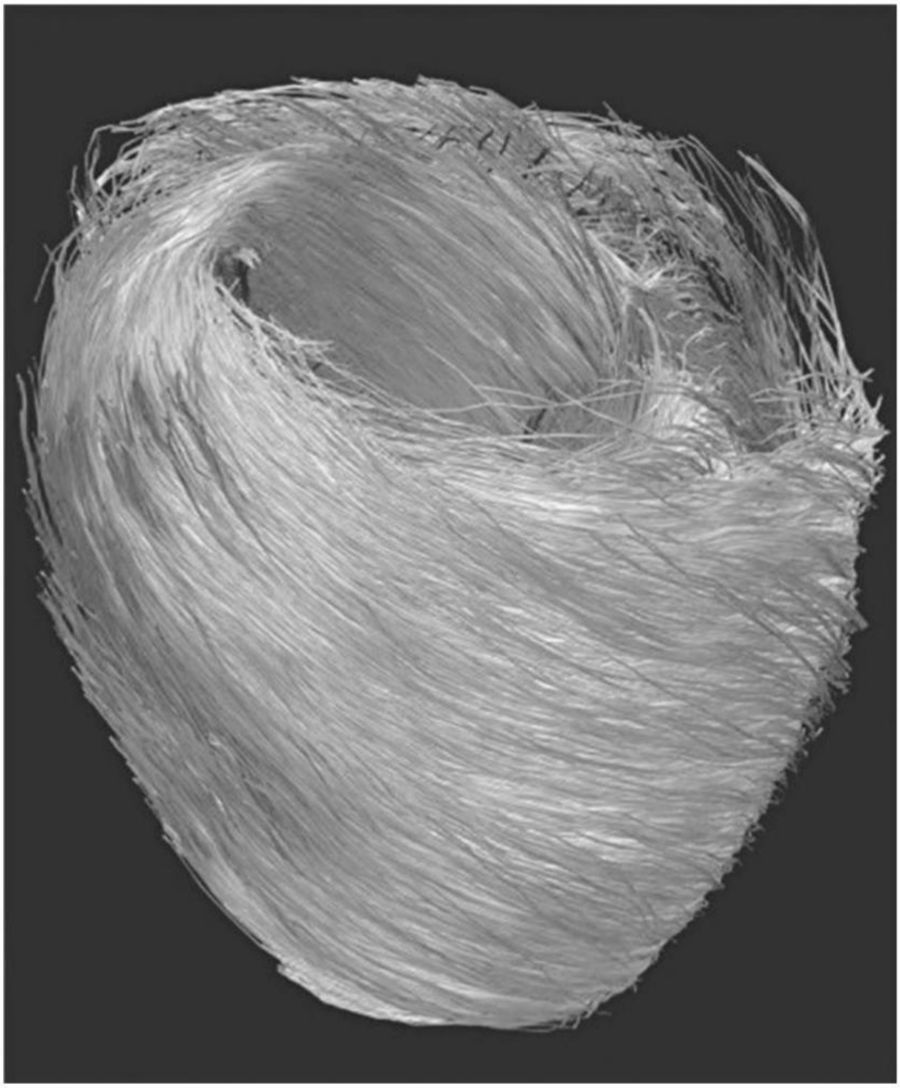
The decisive break with Galen's teachings on the heart was made by William Harvey, who studied medicine at Padua in the early 1600s with teachers in a direct line from Vesalius. Harvey performed some bold if



The heart pumps blood around two circuits of unequal size at the same time. The circuits cross over in the heart in one endless loop, like a lopsided infinity sign or Möbius strip. The heart's larger side, which is situated on the left in all but the one in ten thousand of us, drives the systemic circuit, pumping newly oxygenated blood through the arteries to tissues all around the body. Once in those tissues, the blood unloads oxygen to mobilize cellular respiration,[8] and absorbs carbon dioxide and water, before it returns through the veins to the smaller side of the heart. This smaller side powers the pulmonary circuit, which drives the blood through tiny vessels lining the walls of the lungs where the carbon dioxide and water are released (to be breathed out) even as fresh oxygen is absorbed, returning the blood to the larger side of the heart, where it will be pumped around the body once more. At any one time about 12 per cent of the blood is in the chambers of the heart itself, while 70 per cent is in the systemic circuit and 18 per cent in the pulmonary circuit.

One of the wonders of the heart, says the cardiologist Vivek Muthurangu, is simply that it contracts as strongly and efficiently as it does. An isolated heart muscle cell or cardiomyocyte contracts by around only fifteen per cent each time it twitches, but many in combination give rise to a much greater total contraction in the heart's volume. The general principles behind this are fairly clear: bundles of muscle coil around the heart resulting in a twisting motion that results in an extra squeeze when the chambers contract. But recently scientists have realized that this was not nearly enough to account for the extent of the contraction. It appears that both the micro-and macrostructures in the muscle behave in more complex and subtle ways than was realized. Sheets of muscle may turn on edge as they contract, for example, amplifying the twist of the larger structures of which they are part. The detail of how this all works has yet to be worked out.

Isolated individual heart muscle cells twitch spontaneously and, without a strong external signal to coordinate them, the two billion or so in the walls of the heart are liable to fall out of phase. When they do so the heart goes into fibrillation[9] – chaotic spasms without rhythm – and ceases to pump. The beat that keeps us alive is generated by a natural pacemaker called the sinoatrial node,[10] a group of a few thousand specialized cells in the wall of the heart over the right atrium. To initiate a beat the node contracts, generating an electrical impulse: a signal that it then discharges through the tissues of the heart. The signal travels first to the atria of the heart, causing them to contract. It also travels to a second node, called the atrioventricular, which delays it until the atria have fully contracted. Once they have done so and pushed blood into the ventricles, this second node forwards the signal to the ventricles, causing them to contract in turn.



MRI of heart fibres

The signal from the sinoatrial node is strong enough to initiate this because all its cells fire at exactly the same time. This is an example of synchrony, a phenomenon that occurs across a wide range of living and non-living systems. In all such cases, individual oscillators are coupled through physical, chemical or – as in the heart – electrochemical processes that allow them to influence one another in a sufficiently short period of time. In non-living systems, synchrony can be brought about by forces ranging from tiny vibrations (which explains the tendency of pendulum clocks or mechanical metronomes placed on the same table top to fall into line) to gravity across empty space (which accounts for certain planetary orbits). In the living world, one of the most remarkable examples besides the heart is said to be fireflies flashing in unison for miles along riverbanks in tropical Southeast Asia at night. The mathematician Steven Strogatz writes that he finds this 'beautiful and strange in a way that can only be described as religious ... a wonderful and terrifying thing, [touching us] at a primal level'. Such spontaneous emergent order, he

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