New Scientist

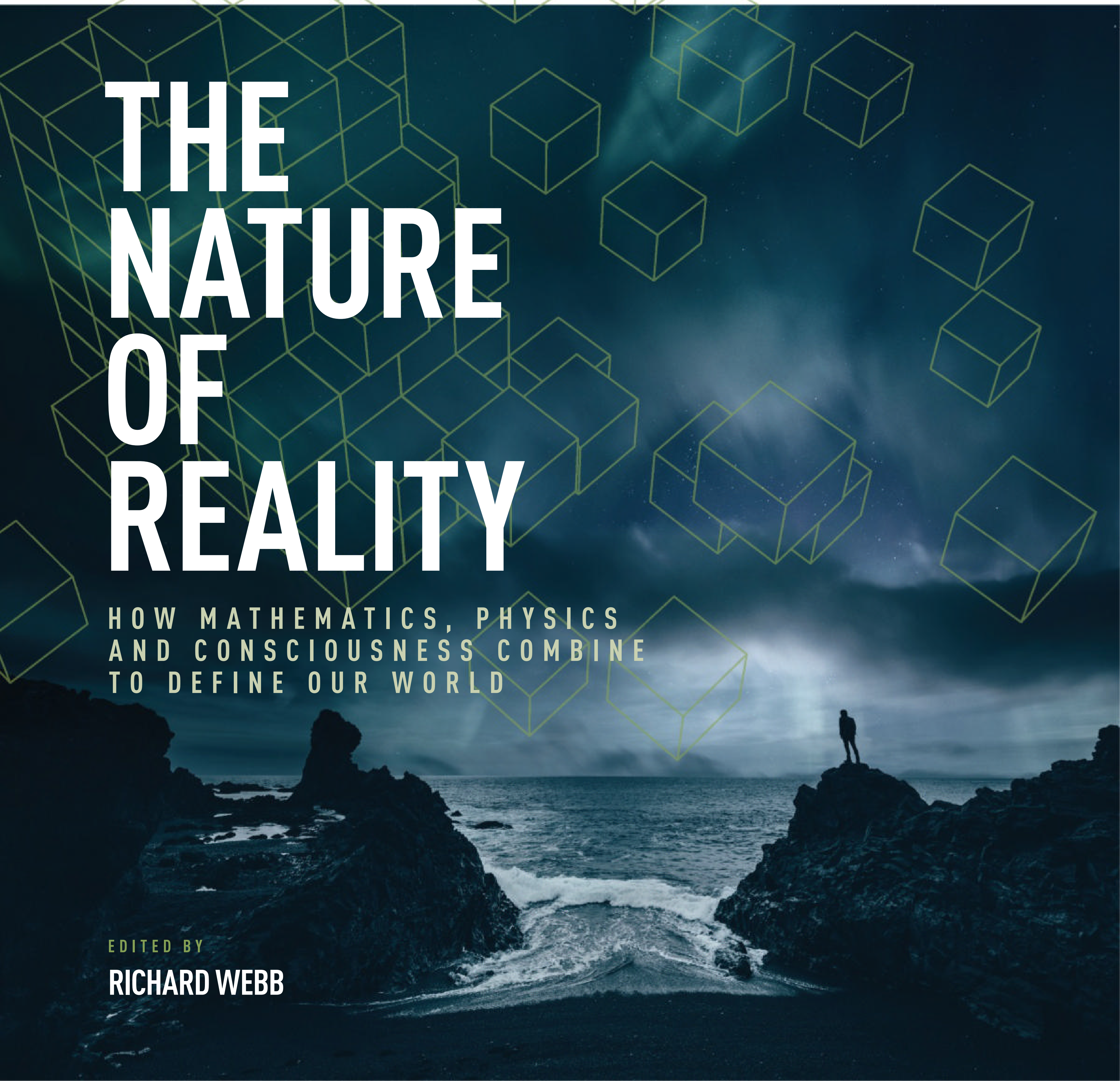
ESSENTIAL GUIDE Nº1

WITH CONTRIBUTIONS FROM

BRIAN GREENE
STEPHEN HAWKING
ROGER PENROSE
AND MORE

THE NATURE OF REALITY

HOW MATHEMATICS, PHYSICS AND CONSCIOUSNESS COMBINE TO DEFINE OUR WORLD



EDITED BY

RICHARD WEBB

NEW SCIENTIST ESSENTIAL GUIDE

THE NATURE OF REALITY

Welcome to the very first edition in a new series, the *New Scientist Essential Guides*. Published five or six times a year, and derived from material originally published in *New Scientist* magazine, we hope they will build up to a collectible library bringing you what you need to know about the hottest areas in science, technology and medicine in a digestible format that still allows for intellectual depth.

The nature of reality is admittedly an ambitious choice of topic to kick this series off with. The subject has challenged knowledge-seekers of many stripes for millennia, and it is fair to say that the more we have learned, the more we realise we still have to learn. We can only hope to scratch the surface here, giving a flavour of how developments over the past century or so in mathematics, fundamental physics and in studies of our own cognition have reshaped the terms of the debate.

We hope you find this first *New Scientist Essential Guide* a stimulating read. Feedback is welcome at essentialguides@newscientist.com. The next edition, on artificial intelligence, will be available from early June. *Richard Webb*

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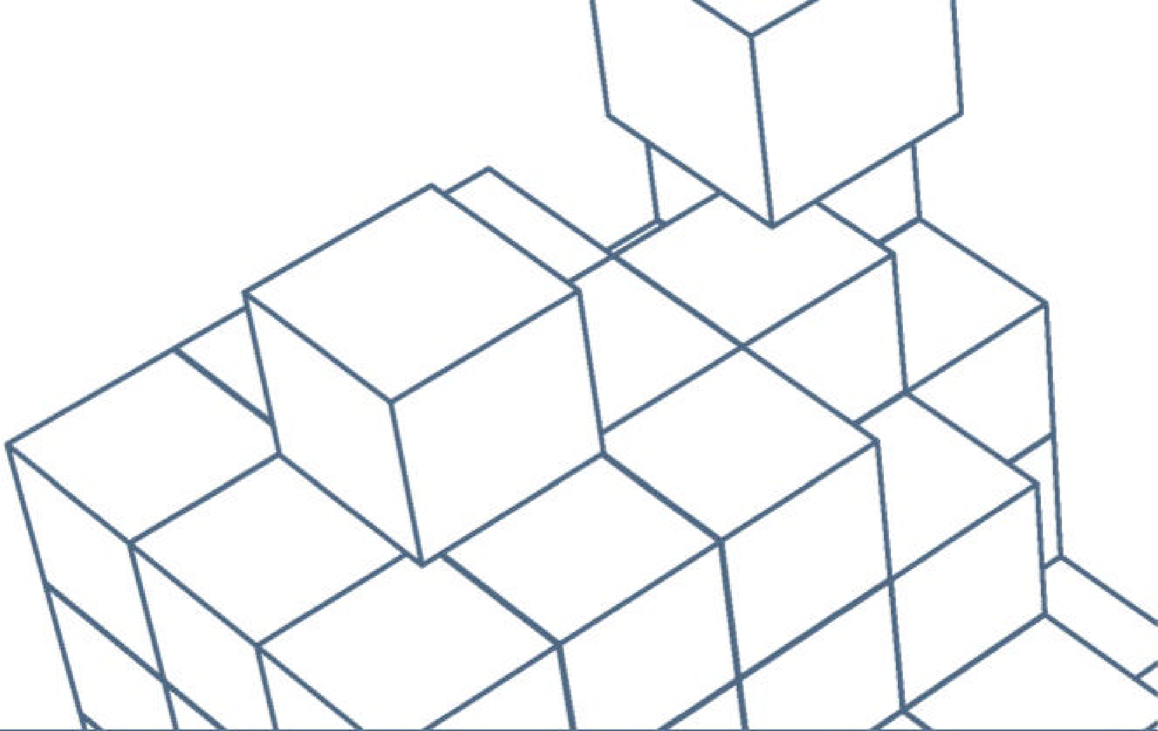


CHAPTER 1

WHAT IS REALITY?

We humans have a bit of a problem with reality. We experience it all the time, but struggle to define it, let alone understand it. In this introductory chapter, renowned physicist and cosmologist Roger Penrose sets the scene, with his take on how mathematics, physical theories and our own perceptions might come together to construct our reality.

CHAPTER 2

THE MATHEMATICAL UNIVERSE

The fact that we live in an intelligible universe is itself a huge mystery. At its heart lies the power of physical laws, rooted in mathematics, to characterise and predict its workings, as cosmologist Brian Greene sets out.

PLUS

CHAPTER 3

ELEMENTS OF REALITY

Every civilisation has its creation story – and our scientifically rooted one starts in the big bang 13.8 billion years ago. The material universe started as quantum fluctuations in the event's immediate aftermath, as the late cosmologist Stephen Hawking writes, and the aim of our physical theories is to explain the evolution of reality since, and the elements that construct it.

PLUS

CHAPTER 4

THE QUANTUM WORLD

Our basic picture of material reality today is underpinned by quantum theory – but the portrait it reveals is so strange that it leaves us wondering whether matter is even real, as philosopher Jan Westerhoff explains.

PLUS

CHAPTER 5

REALITY AND US

Attempts to get a grip on external reality through mathematically based physical laws leave a big factor out of the equation: ourselves. Everything we see is filtered through our perceptions, leading to the question, says cognitive scientist Donald Hoffman, of whether anything we perceive is real at all.

PLUS

CHAPTER 6

IS ANYTHING ACTUALLY REAL?

Implicit in most discussions about reality is the idea that it is somehow a "natural" construct, with laws set elsewhere that are ours to uncover. Philosopher Nick Bostrom has a rather different idea – reality is made by us, or people like us. Welcome to reality: it's all a huge simulation.

CHAPTER 1

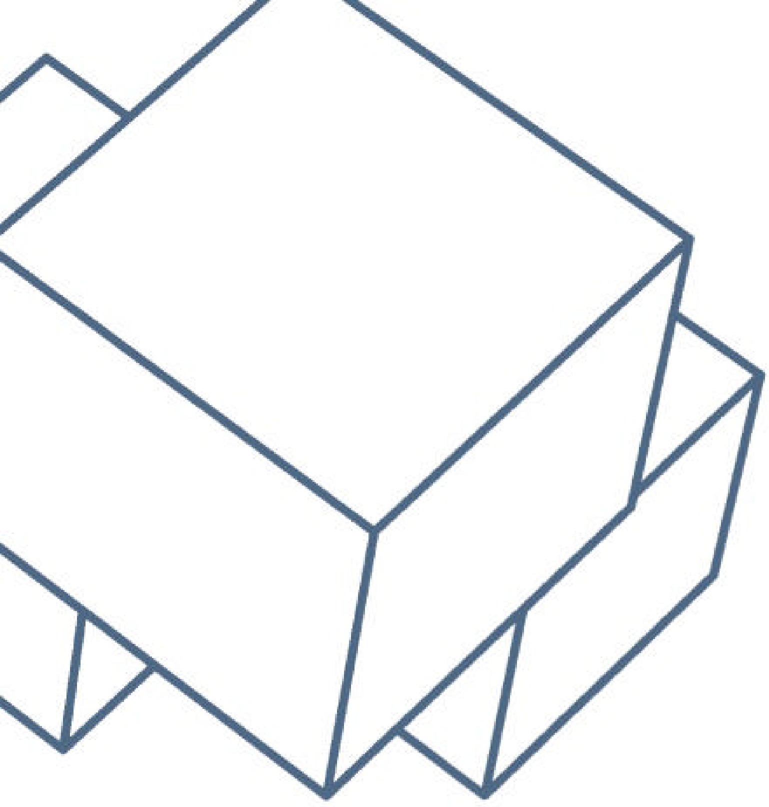
WHAT IS REALITY?

We humans have a bit of a problem with reality. We experience it all the time, but struggle to define it, let alone understand it.

It seems so solid and yet, when we examine it closely, it melts away like a mirage. We don't know when it began, how big it is, where it came from or where it is going, and we certainly don't know why it exists.

Finding answers was once exclusively the purview of philosophers and theologians. But over the past few centuries, scientists in many disciplines, from fundamental physics to neuroscience, have done ever more to peel back its many layers – even if we still aren't entirely sure what we have revealed.

In the chapters that follow, we will explore the various elements of reality, the fundamental physics that underlies our understanding of it, and how the reality around us interfaces with the reality inside our heads. To set the scene, distinguished physicist Roger Penrose sets out some ideas about how these things might interrelate.



PROFILE
ROGER PENROSE

Roger Penrose is a theoretical physicist and cosmologist, and emeritus professor at the University of Oxford, UK. Working with Stephen Hawking and many others, he has made seminal contributions to our understanding of the universe based on Einstein's general relativity, and also worked extensively on the connections between human consciousness, the laws of physics and the nature of reality. He is the author of many books including *The Emperor's New Mind* and *The Road to Reality: A complete guide to the laws of the universe*

WHAT do we understand by "reality"? For those of us who consider ourselves hard-headed realists, there is a kind of common-sense answer: "Reality consists of those things – tables, chairs, trees, houses, planets, animals, people and so on – which are actual things made of matter". We might tend to include some more abstract-seeming notions such as space and time, and the totality of all such "real" things would be referred to as "the universe".

Some might well consider that this is not the whole of reality, however. In particular, there is the question of the reality of our minds. Should we not include a conscious experience as something real? And what about concepts such as truth, virtue or beauty? Of course, some hard-headed people might adopt a doggedly materialist point of view and take mentality and all its attributes to be secondary to what is materially real. Our mental states, after all (so it would be argued), are simply emergent features of the construction and behaviour of our physical brains. We behave in certain ways merely because our brains act according to physical laws – the same laws as those that are strictly obeyed by all other pieces of physical material. Conscious mental experience, accordingly, has no further reality than that of the material underlying its existence; though not yet properly understood, it is merely an "epiphenomenon", having no additional influence on the way that our bodies behave beyond what those physical laws demand.

Some philosophers might take an almost opposite view, arguing that it is conscious experience itself ›

ANXO VIZCAÍNO

that is primary. From this perspective, the "external reality" that appears to constitute the ambient environment of this experience is to be understood as a secondary construct that is abstracted from conscious sense-data. Some might even feel driven to the view that one's own particular conscious experience is to be regarded as primary, and that the experiences of others are themselves merely things to be abstracted, ultimately, from one's own sense-data.

I have considerable difficulty with such a picture of reality, which seems to me lopsided. At best, it would be difficult to convince anyone else of a theory of reality that depended upon such solipsism for its basis. Moreover, I find it extremely hard to see how the extraordinary precision that we seem to observe in the workings of the natural world should find its basis in the musings of any individual.

→ For more on the relationship between reality and us, turn to chapter 5

Even if such a solipsistic basis is not adopted, so that the totality of all conscious experience is to be taken as the primary reality, I still have great difficulty. This would seem to demand that "external reality" is merely something that emerges from some kind of majority-wins voting amongst the individual conscious experiences of all of us taken together. I cannot see that such an emergent picture could have anything like the robustness and precision that we seem to see outside ourselves, stretching away seemingly endlessly in all directions in space and in time, and inwards to minute levels that we do not directly perceive with our senses; all requiring many different kinds of precision instruments to explore the universe over a vast range of different scales. True, there is a mystery about consciousness itself, and it is profoundly puzzling how it could come about from the seemingly purely calculational, unfeeling and utterly impersonal laws of physics that appear to govern the behaviour of all material things. Nevertheless, among the basic laws of physics that we know – and we do not yet know all of them – some are precise to an extraordinary degree, far beyond the precision of our direct sensory experiences, or of the combined calculational powers of all conscious individuals within the ken of mankind.

One example of an over-reachingly deep and precise physical theory is Einstein's magnificent general theory of relativity, which improves even upon the already amazingly accurate Newtonian theory of gravity. In the behaviour of the solar system, Newton's theory is precise to something like one part in 10^7: Einstein's theory does much more, giving not only corrections to Newton's theory that become relevant when gravitational fields get large, but also predicting completely new effects, such as black holes, gravitational lensing and gravitational waves – the analogues, for gravitation, of the light waves of Maxwell's electromagnetic theory.

The agreement between theory and experiment here has been extraordinary. Astronomers have, for example, been monitoring the orbits of one double neutron star system – known as PSR 1913+16 – since the 1970s. The emission of Einstein's predicted

“What substance does the ‘reality’ around us actually have?”

gravitational waves from this system has been confirmed, and there was agreement between the signals received from space and the overall predictions of Einstein’s theory to an astonishing 14 decimal places, even before the LIGO collaboration first directly detected a passing gravitational wave in 2015. At the other end of the size scale, there are multitudes of very precise observations that give innumerable confirmations of the accuracy of quantum theory and also of its generalisation to the quantum theory of relativistic fields, which gives us quantum electrodynamics, one of the underpinnings of the standard model of particle physics. The magnetic moment of an electron, for example, has been precisely measured to some 12 decimal places, and the observed figures are matched precisely by the theoretical predictions of quantum electrodynamics.

→
For more on the physical theories of the elements of reality, see chapter 3

An important point to be made about these physical theories is that they are not just enormously precise but depend upon mathematics of very considerable sophistication. It would be a mistake to think of the role of mathematics in basic physical theory as being simply organisational, where the entities that constitute the world just behave in one way or another, and our theories represent merely our attempts – sometimes very successful – to make some kind of sense of what is going on around us. In such a view there would be no particular mathematical order to the world; it would be we who, in a sense, impose this order by describing, in an elaborate mathematical scheme, those aspects of the world’s behaviour that we can make sense of.

To me, such a description again falls far short of explaining the extraordinary precision in the agreement between the most remarkable of the physical theories that we have come across and the behaviour of our material universe at its most fundamental levels. Take the example of gravitation again. Newton’s beautifully simple mathematical description was later found to remain accurate to a degree tens of thousands of times greater than the observational precision available in the 17th century when he formulated it. Newton had needed to introduce the procedures of calculus in order to formulate his theory. In the 20th century, Einstein added the sophistication of differential geometry – and increased the agreement between theory and observation by a factor of around 10 million. In each case, the increased accuracy was not the result of a new theory being introduced only to make sense of vast amounts of new data. The extra precision was seen only after each theory had been produced, revealing accord between physical behaviour at its deepest level and a beautiful, sophisticated mathematical scheme.

If, as this suggests, the mathematics is indeed there in the behaviour of physical things and not merely imposed by us, then we must ask again what substance does this “reality” that we see about us actually have? What, after all, is the real table that I am now sitting at actually composed of? It is made of wood, yes, but what is wood made of? Well, fibres that ›

“Many quantum theorists would say we should abandon any notion of reality”

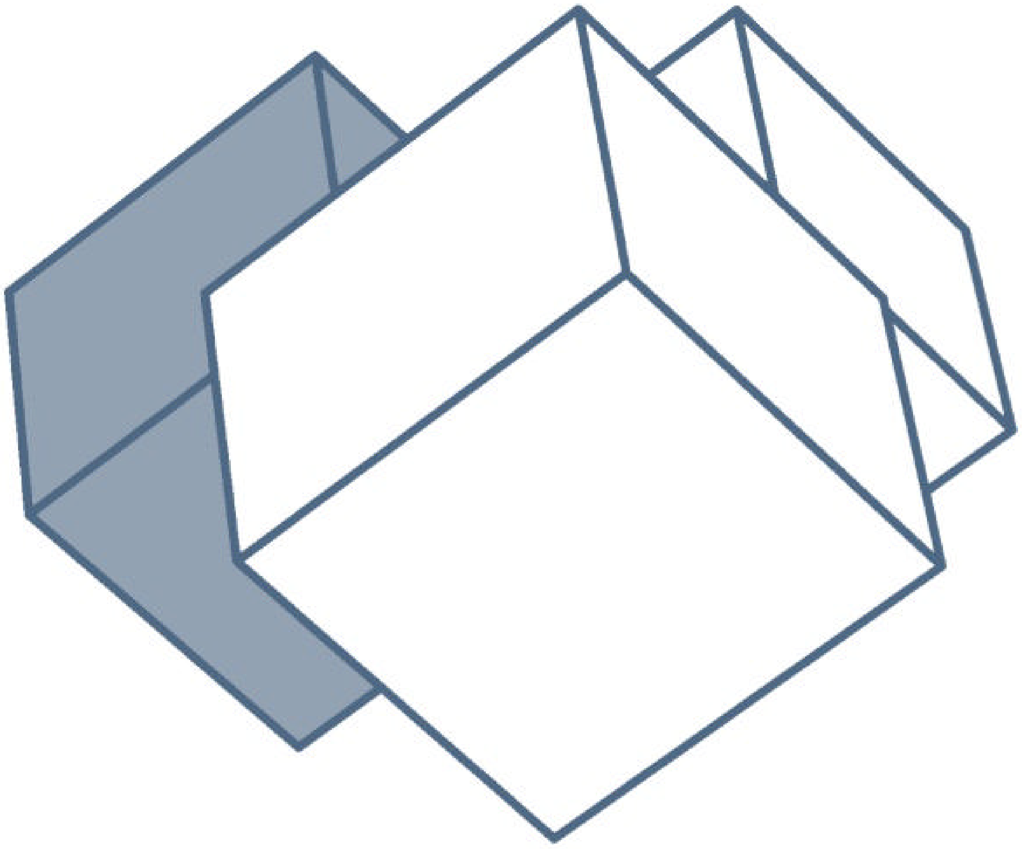
were once living cells. And these? Molecules that are composed of individual atoms. And the atoms? They have their nuclei, built from protons and neutrons and glued together by strong nuclear forces; these nuclei are orbited by electrons, held in by the considerably weaker electromagnetic forces. Going deeper, protons and neutrons are to be thought of as composed of more elementary ingredients, quarks, held together by further entities called gluons. Just what are electrons, quarks and so on, though? The best we can do at this stage is simply to refer to the mathematical equations that they satisfy, which for electrons and quarks would be the Dirac equation. What distinguishes a quark from an electron would be their very different masses and the fact that quarks indulge in interactions – namely the “strong” interactions – that electrons are blind to. What, then, are gluons? They are “gauge” particles that mediate the strong force – which is again a notion that can only be understood in terms of the mathematics used to describe them.

Even if we accept that an electron, say, should be understood as being merely an entity that is the solution of some mathematical equation, how do we distinguish that electron from some other electron? Here a fundamental principle of quantum mechanics comes to our rescue. It asserts that all electrons are indistinguishable from one another: we cannot talk of this electron and that electron, but only of the system, which consists of a pair of electrons, say, or a triple or a quadruple, and so on. Something very similar applies to quarks or gluons or to any other specific kind of particle. Quantum reality is strange that way.

Indeed, quantum reality is strange in many ways. Individual quantum particles can, at one time, be in two different places – or three, or four, or spread out throughout some region, perhaps wiggling around like a wave. Indeed, the “reality” that quantum theory seems to be telling us to believe in is so far removed from what we are used to that many quantum theorists would tell us to abandon the very notion of reality when considering phenomena at the scale of particles, atoms or even molecules.

→ Turn to chapter 4 for a deeper dive into quantum reality

This seems rather hard to take, especially when we are also told that quantum behaviour rules all phenomena, and that even large-scale objects, being built from quantum ingredients, are themselves subject to the same quantum rules. Where does quantum non-reality leave off and the physical reality that we actually seem to experience begin to take over? Present-day quantum theory has no satisfactory answer to this question. My own viewpoint concerning this – and there are many other viewpoints – is that present-day quantum theory is not quite right, and that as the objects under consideration get more massive then the principles of Einstein’s general relativity begin to clash with those of quantum mechanics, and a notion of reality that is more in accordance with our experiences will begin to emerge. The reader should be warned, however: quantum mechanics as it stands has no



accepted observational evidence against it, and all such modifications remain speculative. Moreover, even general relativity, involving as it does the idea of a curved space-time, itself diverges from the notions of reality we are used to.

Whether we look at the universe at the quantum scale or across the vast distances over which the effects of general relativity become clear, then, the common-sense reality of chairs, tables and other material things would seem to dissolve away, to be replaced by a deeper reality inhabiting the world of mathematics. Our mathematical models of physical reality are far from complete, but they provide us with schemes that model reality with great precision – a precision enormously exceeding that of any description that is free of mathematics. There seems every reason to believe that these already remarkable schemes will be improved upon and that even more elegant and subtle pieces of mathematics will be found to mirror reality with even greater precision. Might mathematical entities inhabit their own world, the abstract Platonic world of mathematical forms? It is an idea that many mathematicians are comfortable with. In this scheme, the truths that mathematicians seek are, in a clear sense, already "there", and mathematical research can be compared with archaeology; the mathematicians' job is to seek out these truths as a task of discovery rather than one of invention. To a mathematical Platonist, it is not so absurd to seek an ultimate home for physical reality within Plato's world.

This is not acceptable to everyone. Many philosophers, and others, would argue that mathematics consists merely of idealised mental concepts, and, if the world of mathematics is to be regarded as arising ultimately from our minds, then we have reached a circularity: our minds arise from the functioning of our physical brains, and the very precise physical laws that underlie that functioning are grounded in the mathematics that requires our brains for its existence. My own position is to avoid this immediate paradox by allowing the Platonic mathematical world its own timeless and locationless existence, while allowing it to be accessible to us through mental activity. My viewpoint allows for three different kinds of reality: the physical, the mental and the Platonic-mathematical, with something (as yet) profoundly mysterious in the relations between the three.

We do not properly understand why it is that physical behaviour is mirrored so precisely within the Platonic world, nor do we have much understanding of how conscious mentality seems to arise when physical material, such as that found in wakeful healthy human brains, is organised in just the right way. Nor do we really understand how it is that consciousness, when directed towards the understanding of mathematical problems, is capable of divining mathematical truth. What does this tell us about the nature of physical reality? It tells us that we cannot properly address the question of that reality without understanding its connection with the other two realities: conscious mentality and the wonderful world of mathematics. ■

↓
Read on for more on the role of mathematics in creating reality

CHAPTER 2

THE MATHE-MATICAL UNIVERSE

"The eternal mystery of the world is its comprehensibility... the fact that it is comprehensible is a miracle." The author of those words, Albert Einstein, was expressing a remarkable truth about our reality that we began to explore in the previous chapter: the existence of precise, mathematical laws that have predictive power, and so seem to express some form of objective truth about the world.

This realisation brought about a revolution in human knowledge. It is a gift that has kept on giving, as over the past few centuries physicists have followed their noses – and mathematics – to an ever more accurate understanding of reality.

That quest is far from over, and the deeper questions of why mathematics is so effective, and what mathematics itself consists of, remain mysterious. Theoretical physicist Brian Greene takes up the story.

IN THE late 1800s, when James Clerk Maxwell realised that light was an electromagnetic wave, his equations showed that light's speed should be about 300,000 kilometres per second. This was close to the value experimenters had measured, but Maxwell's equations left a nagging loose end: 300,000 kilometres per second relative to what? At first, scientists pursued the makeshift resolution that an invisible substance permeating space, the "aether", provided this unseen standard of rest.

It was Einstein who in the early 20th century argued that scientists needed to take Maxwell's equations more seriously. If Maxwell's equations did not refer to a standard of rest, then there was no need for a standard of rest. Light's speed, Einstein forcefully declared, is 300,000 kilometres per second relative to anything. The details are of historical interest, but I'm describing this episode for a larger point: everyone had access to Maxwell's mathematics, but it took the genius of Einstein to embrace it fully. His assumption of light's absolute speed allowed him to break through first to the special theory of relativity – overturning centuries of thought regarding space, time, matter and energy – and eventually to the general theory of relativity, the theory of gravity that is still the basis for our working model of the cosmos.

→ For more on how the fundamental principles of physics, see page 34

The story is a prime example of what Nobel laureate Steven Weinberg meant when he wrote: "Our mistake is not that we take our theories too seriously, but that we do not take them seriously enough." Weinberg was referring to another great breakthrough in cosmology, the prediction by Ralph Alpher, Robert Herman and George Gamow of the existence of the cosmic microwave background radiation, the afterglow of the big bang. This prediction is a direct consequence of general relativity combined with basic thermodynamics. But it rose to prominence only after being discovered theoretically twice, a dozen years apart, and then being observed through a benevolent act of serendipity.

To be sure, Weinberg's remark has to be applied with care. Far from every equation with which we theorists tinker rises to that level. In the absence of compelling experimental results, deciding what mathematics should be taken seriously is as much art as it is science.

Einstein was a master of that art. In the decade after his formulation of special relativity in 1905, he became familiar with vast areas of mathematics that most physicists knew little or nothing about. As he groped towards general relativity's final equations, Einstein displayed a rare skill in moulding these mathematical constructs with the firm hand of physical intuition. When he received the news that observations of the 1919 solar eclipse confirmed general relativity's prediction that star light should travel along curved paths, he noted that had the results been different, he "would have been sorry for the dear Lord, since the theory is correct". ›

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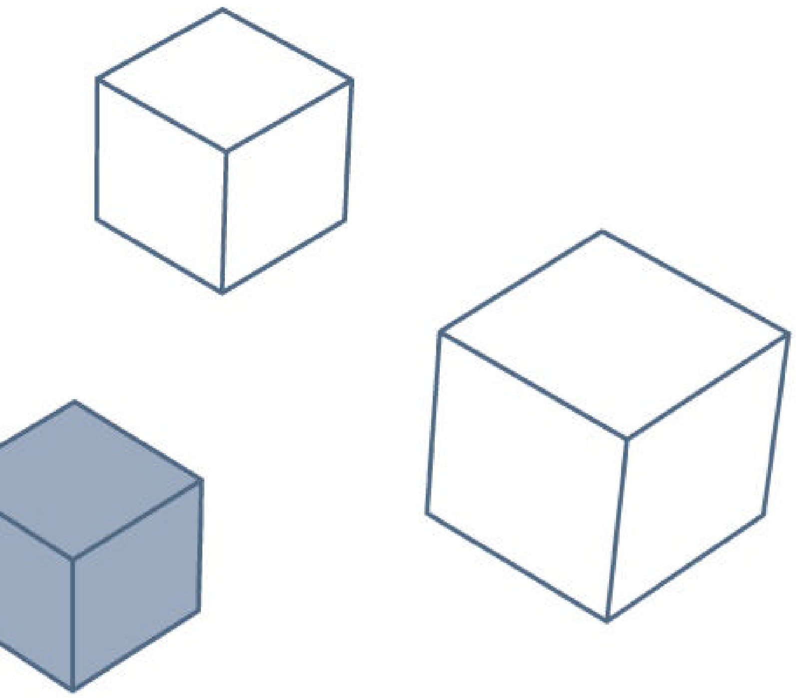


I'm sure that convincing data contravening general relativity would have changed Einstein's tune, but the remark captures well how a set of mathematical equations, through their sleek internal logic, their intrinsic beauty and their potential for wide-ranging applicability, can seemingly radiate reality. Centuries of discovery have made abundantly evident the capacity of mathematics to reveal secreted truths about the workings of the world; monumental upheavals in physics have emerged time and again from vigorously following the lead of mathematics.

Nevertheless, there was a limit to how far Einstein was willing to follow his own mathematics. He did not take the general theory of relativity "seriously enough" to believe its prediction of black holes, or of an expanding universe. Others embraced Einstein's equations more fully than he, and their achievements have set the course of cosmological understanding for nearly a century. Einstein instead in the last 20 years or so of his life threw himself into mathematical investigations, passionately striving for the prized achievement of a unified theory of physics. Looking back, one cannot help but conclude that during these years he was too heavily guided – some might say blinded – by the thicket of equations with which he was constantly surrounded. Even Einstein sometimes made the wrong decision regarding which equations to take seriously and which to not.

Quantum mechanics provides another case study of this dilemma. For decades after Erwin ›

WHEN MATHEMATICS PREDICTS REALITY

Physicist Eugene Wigner coined the phrase "the unreasonable effectiveness of mathematics" in a famous 1969 lecture. It is perhaps most startlingly demonstrated when calculations tell us that something exists in reality that we have never seen before – and the history of modern science is littered with such examples.

ANTIMATTER

In 1928, British physicist Paul Dirac's equation explaining how the electron works predicted the existence of an electron with opposite, positive charge. No one knew what this was – until five years later, when the positron, the first antimatter particle, was discovered in cosmic rays.

PARTICLES GENERALLY

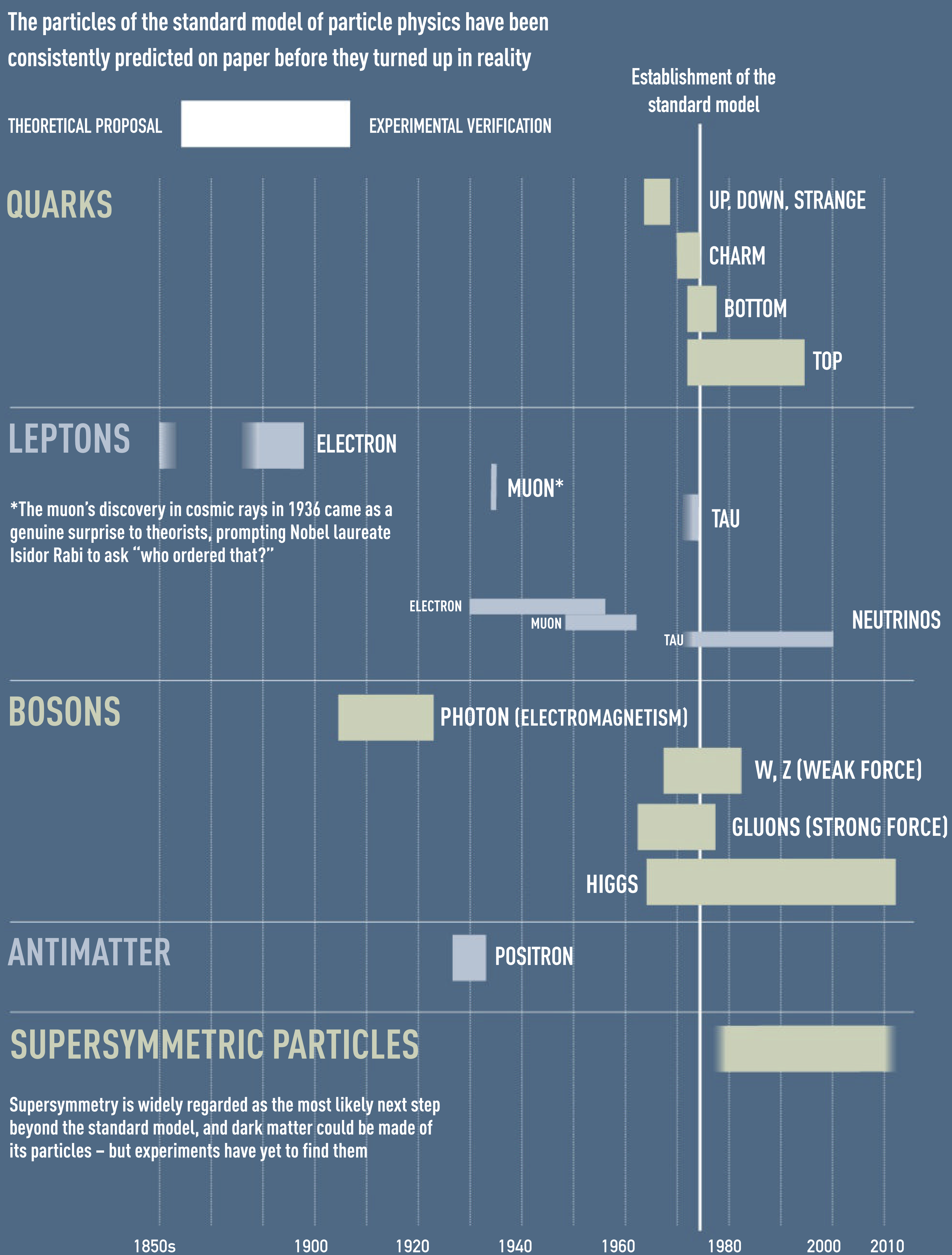
Antimatter set a pattern for particles in the standard model of particle physics being "discovered" theoretically before they popped up in experiments (see diagram, right) - culminating in the discovery of the mass-giving Higgs in 2012, almost a half-century after its existence was first proposed.

THE EXPANDING UNIVERSE

When Albert Einstein completed his general theory of relativity in 1916 he didn't believe its prediction that the universe could shrink or grow. Ignoring what the equations said, he added a "cosmological constant" to keep it static. Just a decade later came evidence of the universe's expansion. In a way, Einstein had the last laugh: in the 1990s, his constant was revived to explain the acceleration of the universe's expansion as a result of dark energy.

IMAGINARY NUMBERS

These numbers are derived by doing the "impossible" – taking the square root of a negative number – and were once thought deserving of their name. They have since popped up all over the place, notably in the description of elementary particles in quantum theory. Reality's conception even of what mathematics is possible seems to differ from our own.


The particles of the standard model of particle physics have been consistently predicted on paper before they turned up in reality
THEORETICAL PROPOSAL
EXPERIMENTAL VERIFICATION
Establishment of the standard model
QUARKS
UP, DOWN, STRANGE
CHARM
BOTTOM
TOP
LEPTONS
ELECTRON
MUON*
*The muon's discovery in cosmic rays in 1936 came as a genuine surprise to theorists, prompting Nobel laureate Isidor Rabi to ask "who ordered that?"
TAU
ELECTRON
MUON
TAU
NEUTRINOS
BOSONS
PHOTON (ELECTROMAGNETISM)
W, Z (WEAK FORCE)
GLUONS (STRONG FORCE)
HIGGS
ANTIMATTER
POSITRON
SUPERSYMMETRIC PARTICLES
Supersymmetry is widely regarded as the most likely next step beyond the standard model, and dark matter could be made of its particles – but experiments have yet to find them
1850s
1900
1920
1940
1960
1980
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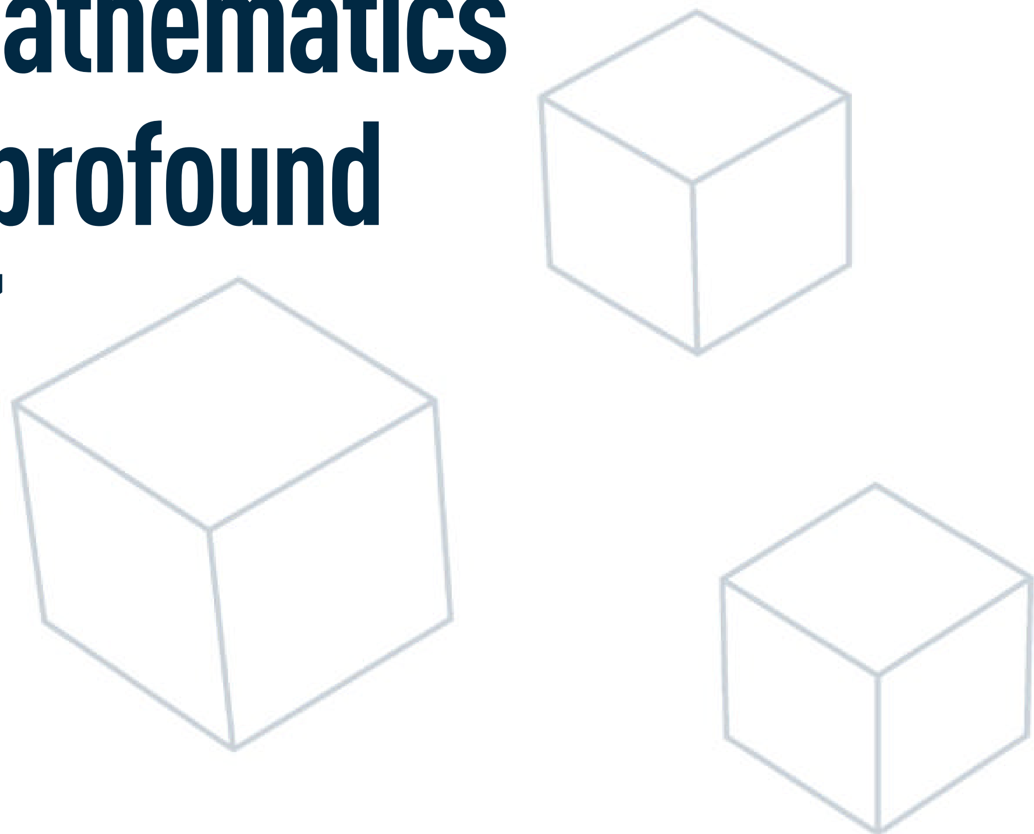
"Following mathematics can lead to profound revelations"



Schrödinger wrote down his equation for how quantum waves evolve in 1926, it was viewed as relevant only to the domain of small things: molecules, atoms and particles. But in 1957, Hugh Everett echoed Einstein's charge of a half century earlier: take the mathematics seriously. Everett argued that Schrödinger's equation should apply to everything because all things material, regardless of size, are made from molecules, atoms and subatomic particles that evolve according to probabilistic rules.

Applying this logic revealed that it is not just experiments that evolve in this way, but experimenters, too. This led Everett to his idea of a quantum "multiverse" in which all possible outcomes are realised in a vast array of parallel worlds.

More than 50 years later, we still do not know if his approach is right. But by taking the mathematics of quantum theory seriously – fully seriously – he may have had one of the most profound revelations of scientific exploration. The multiverse in various forms has since become a pervasive feature of much mathematics that purports to offer us a deeper understanding of reality. In its furthermost incarnation, the "ultimate multiverse", every possible universe allowed by mathematics corresponds to a real universe. Taken to this extreme, mathematics is reality.

→ See page 43 to find out more about the multiverse

Turn to chapter 4 for more on quantum reality

If some or all of the mathematics that has compelled us to think about parallel worlds proves relevant to reality, Einstein's famous query – whether the universe has the properties it does simply because no other universe is possible – would have a definitive answer: no. Our universe is not the only one possible. Its properties could have been different, and indeed the properties of other member universes may well be different. If so, seeking a fundamental explanation for why certain things are the way they are would be pointless. Statistical likelihood or plain happenstance would be firmly inserted in our understanding of a cosmos that would be profoundly vast.

I don't know if this is how things will turn out. No one does. But it is only through fearless engagement that we can learn our limits. Only through rational pursuit of theories, even those that whisk us into strange and unfamiliar domains – by taking the mathematics seriously – do we stand a chance of revealing the hidden expanses of reality. ∎

IS EVERYTHING JUST NUMBERS?

It is one thing to observe that mathematics seems to be very good at describing reality. It is another to suggest that all there is to describe is ultimately just mathematics. But there are good reasons for thinking it could be true – leading us to a very odd conclusion about reality's fundamental make-up.

HOW is it possible that mathematical theories "know" about the existence of Higgs particles or any other feature of physical reality, before they are found in experiments? One answer could be that in some sense mathematics is reality. Perhaps if we dig deep enough, physical objects like tables and chairs are made not of particles, but of numbers.

The idea that our universe is in some sense mathematical has spawned centuries of discussion among physicists and philosophers. In the 17th century, Galileo famously stated that the universe is a "grand book" written in the language of mathematics.

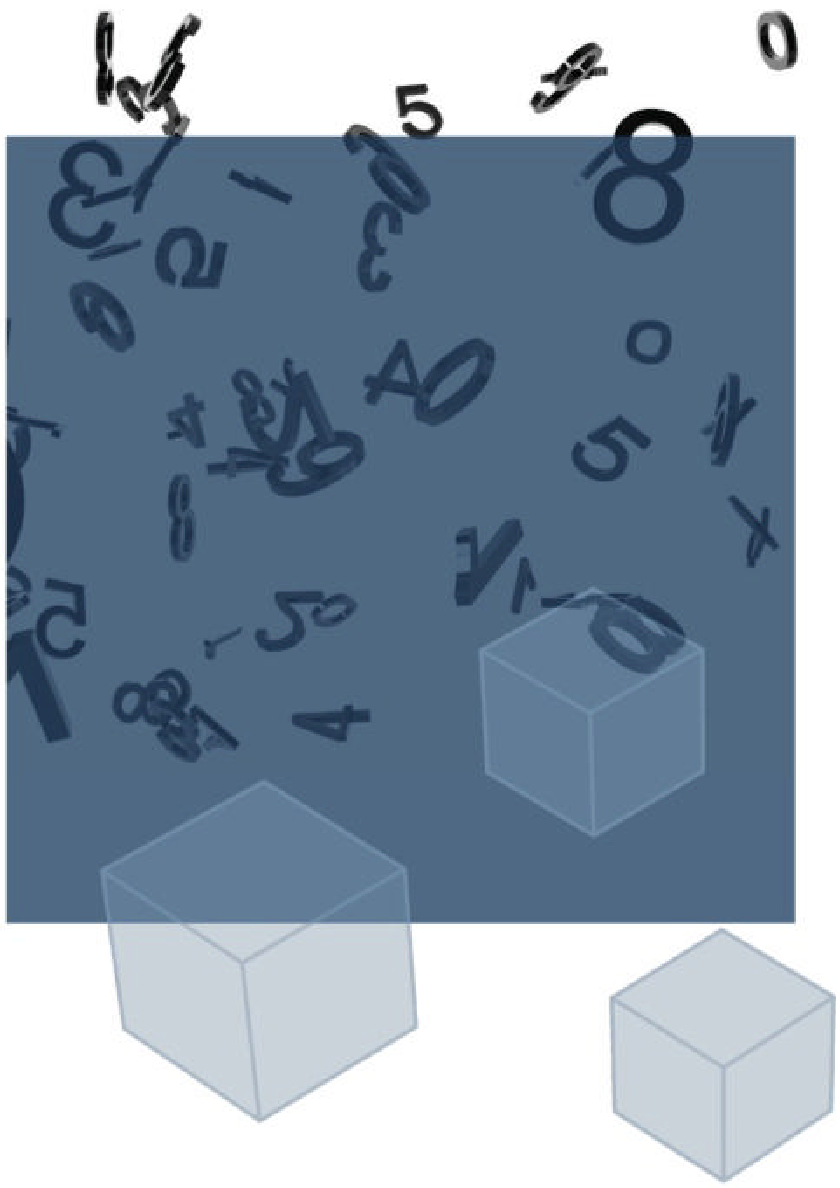
But it is still a big step to say not just that the universe can be described by mathematics, but that it is made of mathematics. This argument has been championed in recent years by Max Tegmark, a physicist at the Massachusetts Institute of Technology. If we assume that reality exists independently of humans, he argues, it must also be well-defined according to non-human entities – aliens or supercomputers, say – that lack any understanding of human concepts.

A description of objects in this reality and the relations between them would have to be completely abstract. Any human-invented words or symbols would have to be mere labels. The only really existing properties of these entities would be those embodied by the relations between them.

To a modern logician, a mathematical structure is precisely this: a set of abstract entities with relations between them. It doesn't matter whether you write "two plus two equals four", "2 + 2 = 4" or "*dos más dos igual a cuatro*". The notation used to denote the entities and the relations is irrelevant; the properties of the integers are embodied by the relations between them.

This idea turns the much-discussed notion of mathematical objects as Platonic objects that exist ›

“The rules of reality might ultimately be derived from nothing”



apart from the material universe somewhat on its head: physical reality is itself a mathematical structure. We all live in a gigantic mathematical object, one more elaborate than a geometrical shape such as a dodecahedron, and more complex than objects with intimidating names like Calabi-Yau manifolds, tensor bundles and Hilbert spaces, which appear in today’s most advanced physical theories. Everything in our world is purely mathematical, including ourselves.

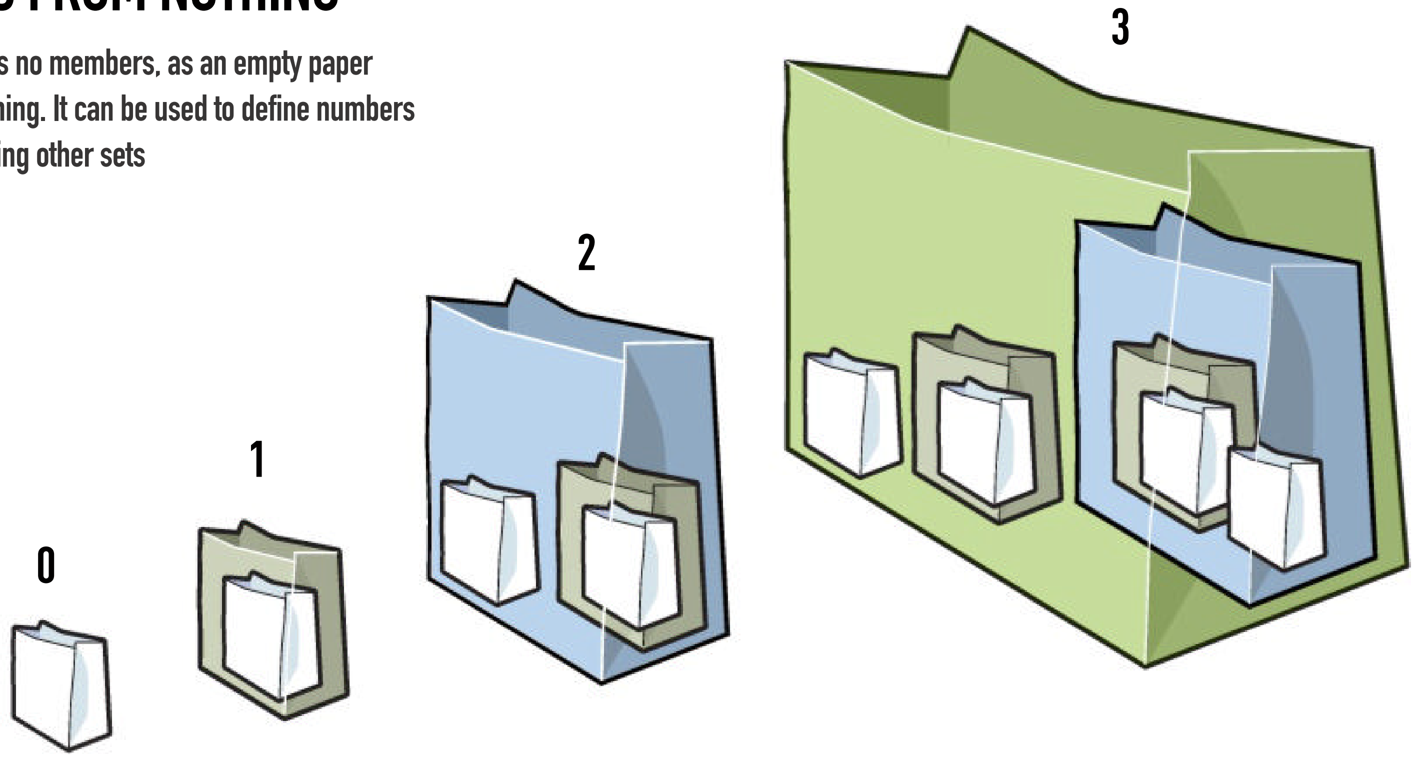
Proceed down this route, and you soon find yourself confronted with a further question: what is mathematics made of? At some level, all of mathematics is built on numbers and the relations between then. So what, then, are numbers? You can show someone two sheep, two coins, two albatrosses, two galaxies. But can you show them two?

Mathematicians solved this problem in the late 19th century with the idea of sets. A set is a collection of mathematical objects – numbers, shapes, functions, networks, whatever. It is defined by listing its members. “The set with members 2, 4, 6, 8” and “the set of even integers between 1 and 9” both define the same set, which can be written as {2, 4, 6, 8}.

Around 1880, mathematician Georg Cantor developed an extensive theory of sets, including, crucially, a way to count how many members a set has,by matching it in a one-to-one fashion with a standard set of a known size. You might count the

NUMBERS FROM NOTHING

The empty set has no members, as an empty paper bag contains nothing. It can be used to define numbers uniquely by forming other sets



number of days in the week by comparing them with a set of known size, that of the dwarfs. Just set up a correspondence: Monday (Doc), Tuesday (Grumpy)... Sunday (Dopey). There are Dopey days in the week.

This alternative number system doesn't itself tell us what a number is, but it gives a way to define "same number". Such considerations led mathematical logicians to realise that to define the number 2, you need to construct a standard set which intuitively has two members. To define 3, use a standard set with three numbers, and so on. But which standard sets to use?

Enter the empty set. Zero is a number, the basis of our entire number system, although its strange properties, such as blowing up when it is divided by itself, meant it took a long time to be recognised as such. It counts the members of a set, the set with no members – that of all mice weighing 20 tonnes, perhaps. Set theory needs θ, as this empty set is written, for the same reason that arithmetic needs 0: things are a lot simpler if you include it. In fact, we can define the number 0 as the empty set – a step that sets a whole new logic in train.

To define the number 1, we need a set with exactly one member. How about making it the set whose only member is the empty set: in symbols, {θ}? Think of a set as a paper bag containing its members. The empty set is an empty paper bag. The set whose only member is the empty set is a paper bag containing an empty paper bag. Which is different: it's got a bag in it. One of them.

IMAGEFLOW/ISTOCKPHOTO

The key step is to define the number 2. We need a uniquely defined set with two members. So why not use the only two sets we've mentioned so far: θ and {θ}? We therefore define 2 to be the set {θ, {θ}}. Which, thanks to our definitions, is the same as {0, 1}.

Now a pattern emerges. We define 3 as {0, 1, 2}, a set with three members, all of them already defined – {θ, {θ}, {θ, {θ}}}, in terms just of the empty set. And so on with rapidly increasing complexity.

The building materials here are abstractions: the empty set and the act of forming a set by listing its members. But the way these sets relate to each other leads to a well-defined construction for the number system, in which each number is a specific set that intuitively has that number of members. Once you've defined the positive whole numbers, similar trickery defines negative numbers, fractions, real numbers (infinite decimals), complex numbers... all the way to the mathematical objects and rules that underlie the physical theories that underpin our understanding of reality.

"Nothing will come of nothing," Shakespeare's King Lear said. Maybe the Bard had it wrong: perhaps indeed everything ultimately comes of nothing. ▮

→ See page 54 for more on the relationship between mathematics and quantum reality

CHAPTER 3

ELEMENTS OF REALITY

We have made remarkable strides in the past century in understanding the physical basis of reality. That's largely down to the development of two theories. Albert Einstein's general theory of relativity provided us with a new conception of gravity, the force that shapes the universe, and became the basis of a new standard model of cosmology. Meanwhile quantum theory spawned the standard model of particle physics, which explains with peerless accuracy the workings of the basic building blocks of nature and the three other fundamental forces that act on them.

But this is by no means a complete picture. Quantum theory and general relativity don't get along, disagreeing on fundamentals such as the nature of space and time, and falling out entirely in situations where both theories come into play, such as during the big bang. Then there are apparitions such as dark matter and dark energy, seemingly called into being by astrophysical observations, that our current theories of reality can't explain.

The late cosmologist Stephen Hawking did perhaps more than any other scientist to investigate the consequences of relativity and its clashes with quantum theory. In this contribution to *New Scientist* from 2011, he takes up our account of the elements of reality – with the story of how it all began.

PROFILE

STEPHEN HAWKING

Stephen Hawking was a theoretical physicist and cosmologist at the University of Cambridge, UK, whose contributions to our understanding of Einstein's universe ranged from investigations of the big bang to theories about the thermodynamics of black holes. He authored books including *A Brief History of Time* and *Brief Answers to the Big Questions*, published shortly after his death in 2018.

WHY are we here? Where did we come from? According to the Boshongo people of central Africa, before us there was only darkness, water and the great god Bumba. One day Bumba, in pain from a stomach ache, vomited up the sun. The sun evaporated some of the water, leaving land. Still in discomfort, Bumba vomited up the moon, the stars and then the leopard, the crocodile, the turtle, and finally, humans.

This creation myth, like many others, wrestles with questions that we all still ask today. Fortunately, we now have a tool to provide the answers: science.

When it comes to these mysteries of existence the first scientific evidence was discovered about 80 years ago, when Edwin Hubble began to make observations in the 1920s with the 100-inch telescope on Mount Wilson in Los Angeles County.

To his surprise, Hubble found that nearly all the galaxies were moving away from us. Moreover, the more distant the galaxies, the faster they were moving away. The expansion of the universe was one of the most important intellectual discoveries of all time.

This finding transformed the debate about whether the universe had a beginning. If galaxies are moving apart now, they must therefore have been closer together in the past. If their speed had been constant, they would all have been on top of one another billions of years ago. Was this how the universe began? At that time many scientists were unhappy with the universe having a beginning because it seemed to imply that physics had broken down. One would have to invoke an outside agency, which for convenience one can call God, to determine how the universe began. They therefore advanced theories in which the universe was expanding at the present time, but didn't have a beginning. Perhaps the best known was proposed in 1948, and called the steady state theory.

According to this theory, the universe would have existed for ever and would have looked the same at all times. This last property had the great virtue of being a prediction that could be tested, a critical ingredient of the scientific method. And it was found lacking.

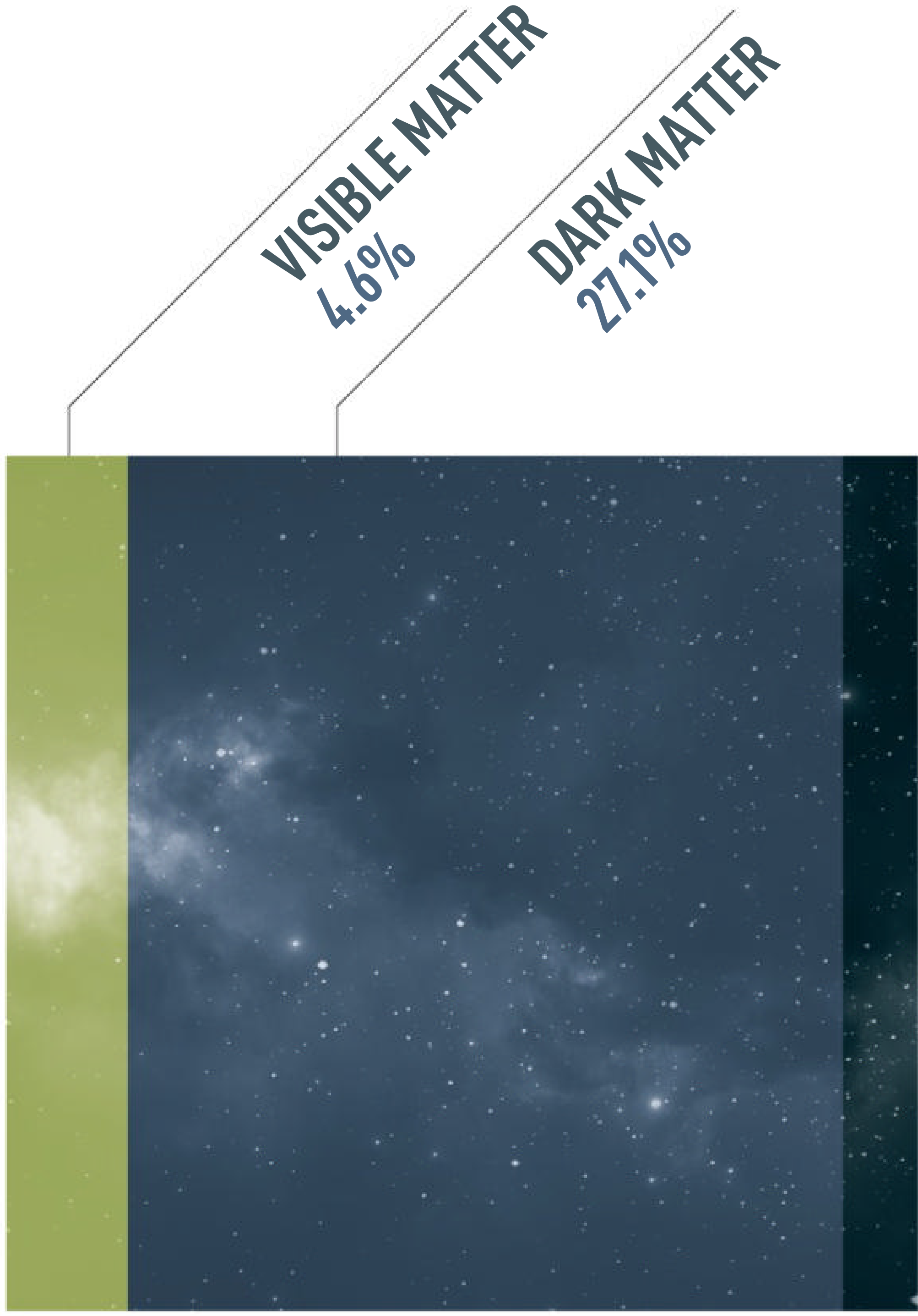
Observational evidence to confirm the idea that the universe had a very dense beginning came in 1965, with the discovery of a faint background of microwaves throughout space. This was thought to be radiation left over from an early hot and dense state. As the universe expanded, the radiation would have cooled until it is just the remnant we see today.

Theory backed this idea. With Roger Penrose, I showed that if Einstein's general theory of relativity is correct, there would be a singularity, a point of infinite density and space-time curvature, where time has a beginning. The universe started off in the big bang, expanding faster and faster. This is called inflation and it turns out that inflation in the early cosmos was much more rapid: the universe doubled in size many times in a tiny fraction of a second.

Inflation made the universe very large and very smooth and flat. However, it was not completely smooth: there were tiny variations from place to place. These variations caused minute differences in the temperature of the early universe, which we can see in the cosmic microwave background. They mean some regions will be expanding slightly less fast. The slower regions eventually stop expanding and collapse again to form galaxies and stars. And, in turn, solar systems.

We owe our existence to these variations. If the early universe had been completely smooth, there would be no stars and so life could not have developed. We are the product of primordial quantum fluctuations. ▮

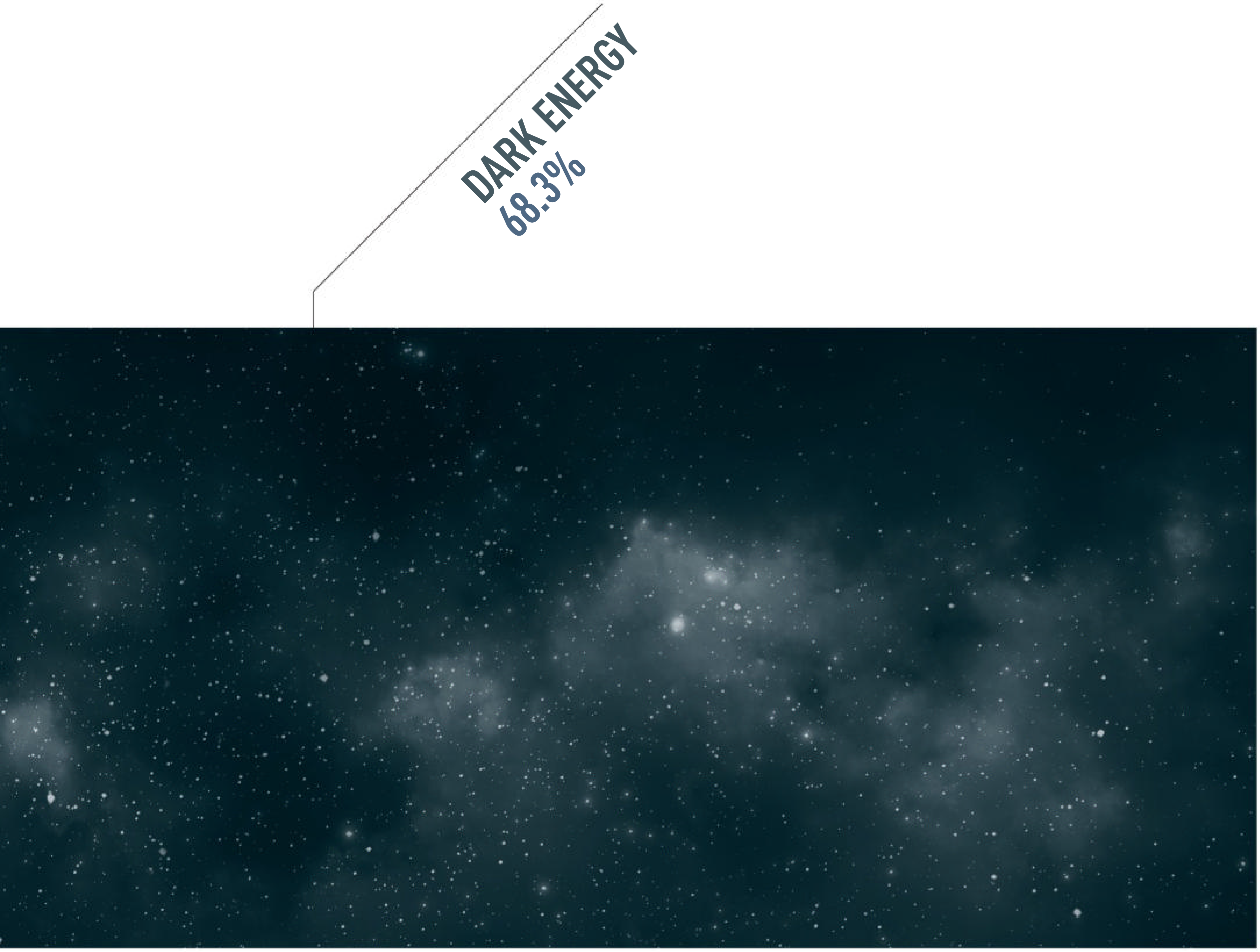
ANXO VIZCAÍNO



WHAT THE UNIVERSE IS MADE OF

In the 13.8 billion years since the big bang, the universe has continued to expand and cool. Gravity has pulled together the stars and galaxies that to our eyes define the universe. But to cosmologists, they are just a dusting of glitter on the true face of space. Two elusive, invisible entities – dark matter and dark energy – appear to together make up more than 95 per cent of all the stuff in the universe. When it comes to explaining large-scale reality, our standard model of cosmology is both a triumph and a huge work in progress.

WHEN Albert Einstein formulated his general theory of relativity, the physical foundation of our standard cosmology, he began with a simple observation: that any object's gravitational mass is exactly equal to its resistance to acceleration, or inertial mass. From this "equivalence principle", he deduced equations that showed how space is warped by mass and motion, and how we see that bending as gravity. Apples fall to Earth because Earth's mass bends space-time.



In a relatively low-gravity environment such as Earth, general relativity's effects look very like those predicted by Newton's earlier theory, which treats gravity as a force that travels instantaneously between objects. With stronger gravitational fields, however, the predictions diverge considerably. One extra prediction of general relativity is that large accelerating masses send out tiny ripples in the weave of space-time called gravitational waves. The first direct detection of such a wave passing through Earth, by the LIGO collaboration in 2015, was a crowning triumph of the theory.

Gravity is the dominant force of nature on cosmic scales, so general relativity is our best tool for modelling how the universe as a whole moves and behaves. But its equations are fiendishly complicated, with a frightening array of levers to pull. If you then give them a complex input, such as the details of the real universe's messy distribution of mass and energy, they become effectively impossible to solve. To make a working model, we have to make the simplifying assumption known as the cosmological principle, that the universe should look pretty much the same everywhere – as indeed it seems to, with stuff distributed pretty evenly when we look at large enough scales.

Einstein's own first pared-down model universe, which he filled with an inert dust of uniform density, turned up a cosmos that contracted under its own gravity. He saw that as a problem, and circumvented it by adding a new term into the equations by which ›

> “The first indications of unseen complications in reality came in the 1930s”

empty space itself gains a constant energy density. Its gravity turns out to be repulsive, so adding the right amount of this “cosmological constant” ensured the universe neither expanded nor contracted. When observations in the 1920s showed it was actually expanding, Einstein described this move as his greatest blunder.

It was left to others to apply the equations of relativity to an expanding universe. They arrived at a model cosmos that grows from an initial point of unimaginable density, and whose expansion is gradually slowed down by matter’s gravity.

This was the birth of big bang cosmology. Back then, the main question was whether the expansion would ever come to a halt. The answer seemed to be no; there was just too little matter for gravity to rein in the fleeing galaxies. The universe would coast outwards forever.

The first indication of unseen complications in this picture came in the 1930s, although it didn’t become fully visible until the late 1970s. That was when astronomer Vera Rubin found that galaxies are spinning too fast. The gravity of the visible matter would be too weak to hold these galaxies together according to general relativity, or indeed plain old Newtonian physics. Her conclusion was that there must be a lot of invisible matter to provide extra gravitational glue.

The existence of dark matter is backed up by other lines of evidence, such as how groups of galaxies move, and the way they bend light on its way to us. It is also needed to pull things together to begin galaxy-building in the first place. Overall, there seems to be about five times as much dark matter as visible gas and stars.

Dark matter’s identity is unknown. It seems to be something beyond the standard model of particle physics, and despite our best efforts we have yet to see or create a dark matter particle on Earth. But it changed cosmology’s standard model only slightly: its gravitational effect in general relativity is identical to that of ordinary matter, and even such an abundance of gravitating stuff is too little to halt the universe’s expansion.

↓
Read on overleaf for more on the particles, fields and forces of physics

In the 1990s came an even more mysterious discovery. Astronomers tracing the expansion of the universe more precisely than ever before, using measurements of explosions called type 1a supernovae, showed that the cosmic expansion is accelerating. It seems some repulsive force, acting throughout the universe, is now comprehensively trouncing matter’s attractive gravity.

This could be Einstein’s cosmological constant resurrected, an energy in the vacuum that generates a repulsive force, although particle physics struggles to explain why space should have the rather small implied energy density. So imaginative theorists have devised other ideas, including energy fields created by as-yet-unseen particles, and forces from beyond the visible universe or emanating from other dimensions.

Whatever it might be, dark energy seems real enough. The cosmic microwave background radiation, released when the first atoms formed just 380,000 years after the big bang, bears a faint pattern of hotter and cooler spots that reveals where the young cosmos was a little more or less dense. The typical spot sizes can be used to work out to what extent space as a whole is warped by the matter and motions within it. It appears to be almost exactly flat, meaning all these bending influences must cancel out. This, again, requires some extra, repulsive energy to balance the bending due to expansion and the gravity of matter. A similar story is told by the pattern of galaxies in space.

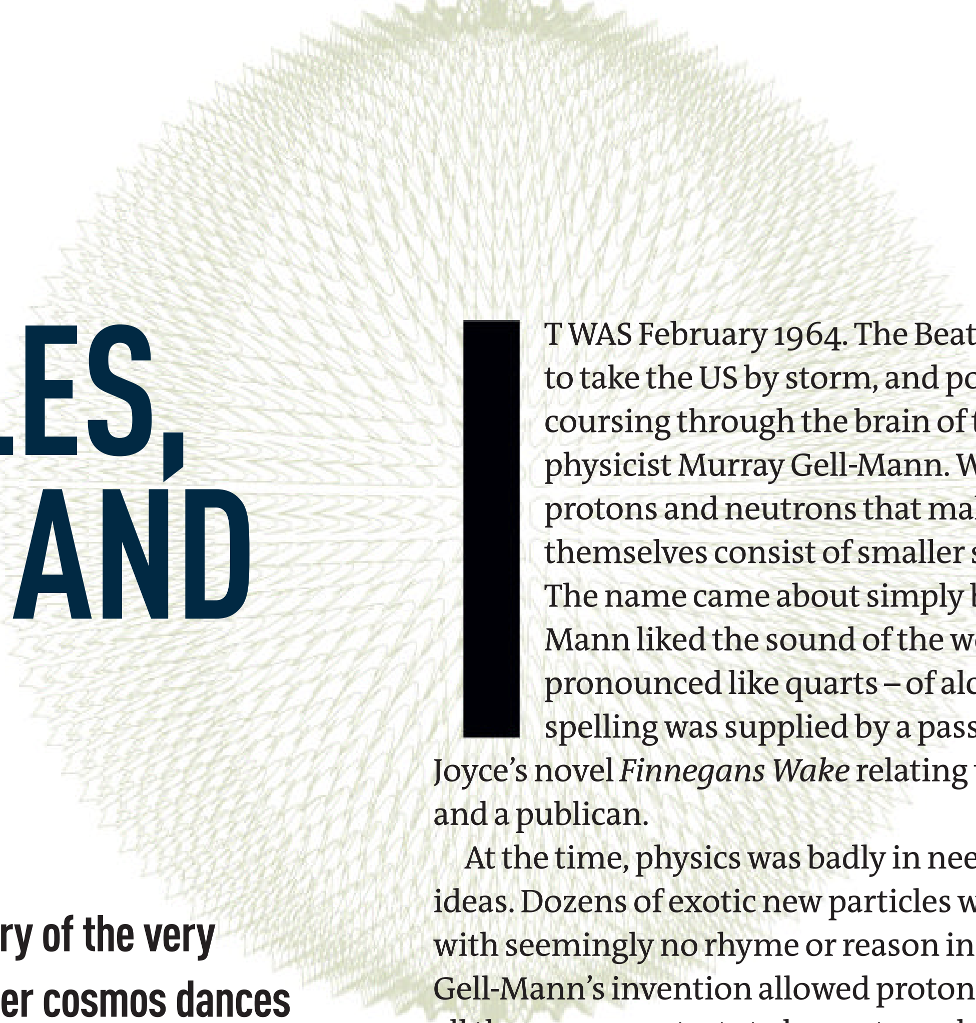
All of this leaves us with a precise recipe for the consituents of material reality on the largest scales. The average density of ordinary matter in space is 0.426 yoctograms per cubic metre (a yoctogram is 10^{-24} grams, and 0.426 of one equates to about 250 protons), and it makes up less than 5 per cent of the total energy density of the universe. Dark matter makes up around 27 per cent, and dark energy just over 68 per cent. Our model of a big-bang universe based on general relativity fits our observations very nicely – as long as we are happy to make 95 per cent of it up.

Arguably, we must invent even more than that. To explain why the universe looks so extraordinarily uniform in all directions, today's consensus cosmology contains a third exotic element. When the universe was just 10^{-36} seconds old, an overwhelming force took over. Called the inflaton field, it was repulsive like dark energy, but far more powerful, causing the universe to expand explosively by a factor of more than 10^{25}, flattening space and smoothing out any gross irregularities.

When this period of inflation ended, the inflaton field transformed into matter and radiation. Quantum fluctuations in the field became slight variations in density, which eventually became the spots in the cosmic microwave background, and today's galaxies. Again, this fantastic story seems to fit the observational facts. And again it comes with conceptual baggage. Inflation is no trouble for general relativity – mathematically it just requires an add-on term identical to the cosmological constant. But at one time this inflaton field must have made up 100 per cent of the contents of the universe, and its origin poses as much of a puzzle as either dark matter or dark energy. What's more, once inflation has started it proves tricky to stop: it goes on to create a further legion of universes divorced from our own – the beginnings of perhaps the biggest, most mind-blowing idea in modern physics: the multiverse.

↓
See page 43 later in this chapter for more on the multiverse

For Robert Kirshner, however, a cosmologist at Harvard University and a member of one of the supernova teams that first exposed dark energy, the successes of Einstein's theory are too manifest for these problems to mean it is completely wrong. "It doesn't mean there is any flaw in our arguments. It gives a sense not of desperation, but inspiration." But as long as we have no evidence of dark matter in the lab, or a proven physical basis for dark energy, or any idea what caused inflation, the possibility remains that we are living under some profound misapprehension – an unknown unknown, something so basic awry in our mathematical model of the universe that as yet we have not been able to imagine the form of our mistake. Might a quantum theory of gravity show us the way forward? Or might some new observation lead us to reformulate our general relativistic cosmology again? It seems unlikely that the last word on cosmic reality has been spoken.



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PARTICLES, FORCES AND FIELDS

If general relativity is a theory of the very large, telling us how the wider cosmos dances to gravity's tune, then quantum theory speaks to the very small and informs the standard model of particle physics. A half-century in the making, this standard model has shown an amazing predictive power – but it too has enough gaps to suggest it might not be the final answer about material reality.

IT WAS February 1964. The Beatles were poised to take the US by storm, and potent stuff was coursing through the brain of theoretical physicist Murray Gell-Mann. What if the protons and neutrons that make up matter themselves consist of smaller stuff: "quarks"? The name came about simply because Gell-Mann liked the sound of the word, which he pronounced like quarts – of alcohol. The spelling was supplied by a passage from James Joyce's novel *Finnegans Wake* relating to seagulls, sex and a publican.

At the time, physics was badly in need of radical ideas. Dozens of exotic new particles were turning up with seemingly no rhyme or reason in cosmic rays. Gell-Mann's invention allowed protons, neutrons and all these new upstarts to be portrayed as combinations of two or three of these more fundamental entities.

The idea was too far out for most physicists. The new particles broke established rules by having fractional electrical charges of +2/3 or -1/3, and could also never be seen alone. Why should reality conform to such a whim?

Alternatively, why shouldn't it? Quarks became a foundation of one of the best-tested theoretical models in all of science: the standard model of particle physics. In four decades, the standard model has demonstrated an uncanny ability to turn theorists' desires into dutifully confirmed reality. The discovery at CERN's Large Hadron Collider in 2012 of the Higgs boson, the particle that gives all other fundamental particles their mass, marked the completion of the standard model – an apparently resounding victory.

The basics of the standard model can be written on a postcard: six quarks arranged into three "generations" of pairs identical in all but mass; six leptons, such as electrons and neutrinos, arranged similarly; and a handful of bosons that transmit nature's fundamental forces between them.

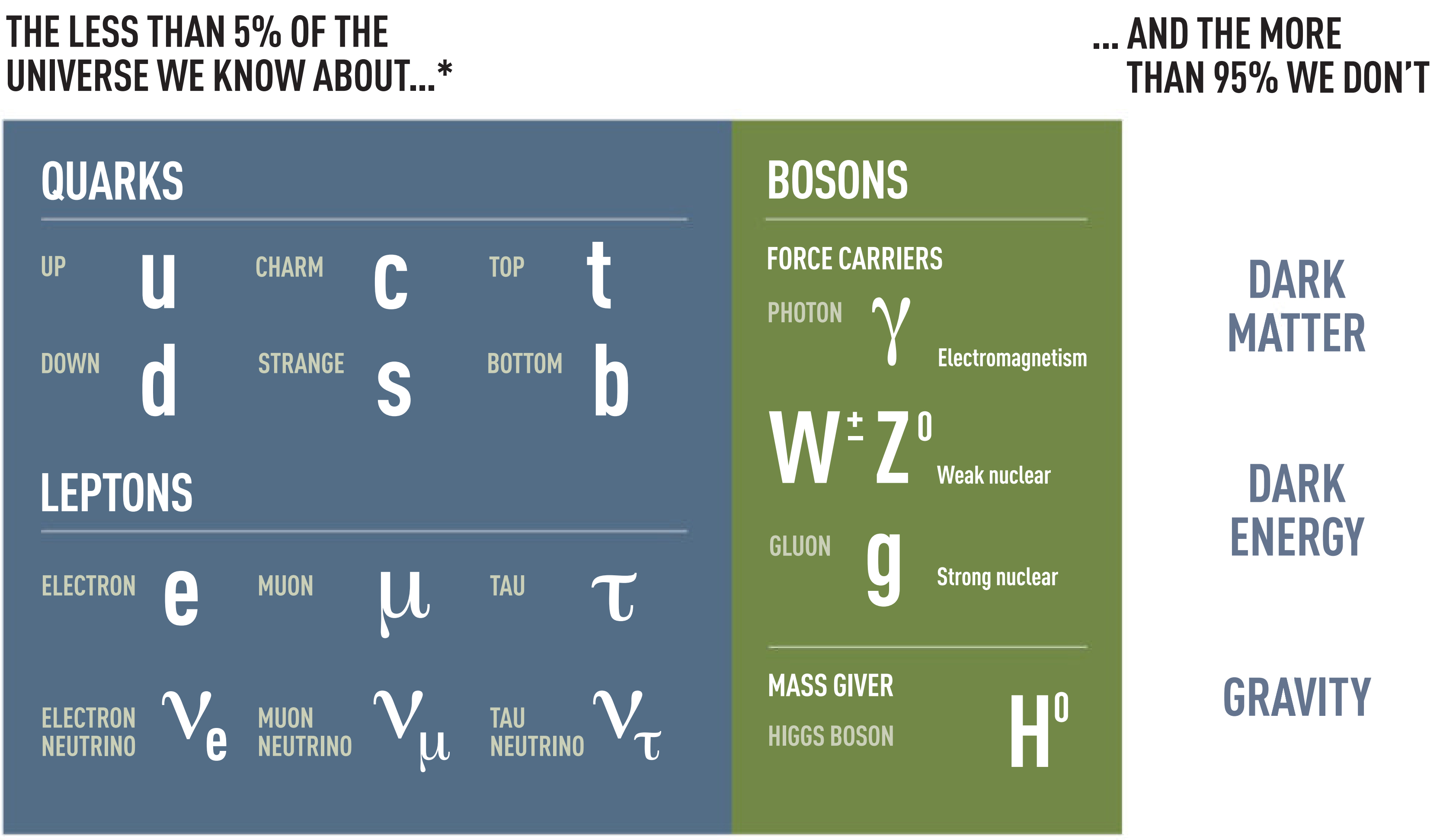
The essential thing about all these entities is that they are quantum particles. Quantum theory grew from radical discoveries at the beginning of the 20th century, which showed that the wavelengths of radiation emitted and absorbed by atoms could be explained only by assuming that energy is bundled in discrete amounts, or "quanta". That unleashed an absurd duality at the smallest scales whereby a particle is also a wave and vice versa. These nebulous wave-particles do not move according to the tidy rules of classical, Newtonian mechanics, but dance to probabilities bounded by bizarre rules in an abstract mathematical space.

→ Turn to chapter 4 for a more thorough investigation of quantum reality

Quantum mechanics was largely in place by the mid 1920s, and it has yet to fail an experimental test. But when in the late 1920s Paul Dirac and others started to hook up quantum mechanics with Einstein's special relativity – a vital step in describing particles that shunt around at near-light speeds – things began to take on a life of their own. Dirac's relativistic equation for the electron had more than one solution, and seemed to predict that a particle existed just like the electron, but with opposite electric charge. The positron duly turned up in cosmic rays five years later. Antimatter had been invented by a theorist's pen.

Quantum field theory, the basis of the standard model, represents the culmination of this logic. The idea of a field transmitting forces goes back to Michael Faraday in the 19th century, but the mathematical structure of quantum fields gives them an odd property: they can create particles from empty space and destroy them again. Thus, according to the theory of quantum electrodynamics, two electrons repel each other thanks to a photon – the quantum particle of the electromagnetic field – that appears from nowhere and passes from one electron to the other. An infinite series of such "virtual" particle fluctuations shift properties of classical or "bare" electrons by tiny amounts – shifts confirmed with stunning accuracy by many experiments since the 1940s.

It took a little longer for quantum theory to tame the other forces. The weak nuclear force, which transmutes one particle into another in radioactive decay, was plagued by unruly infinities that made calculations of all but the simplest effects impossible. The way forward, taken during the 1960s by Weinberg and ›



* for simplicity antiparticles are not shown

others, was to mash it up with electromagnetism into a unified electroweak force that manifests itself at very high energies, such as those in the early universe.

Just as Dirac's equation predicted antimatter, this theory presaged particles that had never been seen: the massive W and Z bosons to transmit today's separated, short-range weak force; and the Higgs boson. The Higgs was needed to ensure that during the breakdown of the unified electroweak force the W and Z particles acquired mass, confining the weak force to atomic distances, while the photons of electromagnetism did not, allowing them to zip across the universe.

At the same time, the quantum field theory of the strong nuclear force, which holds atomic nuclei together, was evolving "from farce to triumph", in the words of the theory's co-inventor David Gross of the University of California, Santa Barbara. Quantum chromodynamics, another term coined by Gell-Mann, finally made quarks respectable by describing their interactions by the exchange of eight gluons that carry a "colour" charge, and showed how, uniquely, this force gets stronger the further you pull two quarks apart. "It could both explain why protons looked as if they were made of quarks and why these quarks could never be pulled out of protons," says Gross.

And that, largely, was it. By 1973, the Beatles had split up and, following a period of mind-boggling theoretical invention, the standard model was in place. There was the unified electroweak theory, to which all particles succumb; and quantum chromodynamics, which affects only quarks and gluons. The model wasn't just clever, it was beautiful. Its equations had a symmetry that dictated the character of nature's forces, and told us what sort of new particles to look for and where.

And, sure enough, the bumps in particle-collider data soon began to appear – together with goosebumps on the skin of the theorists. Evidence for three quarks had already been established in experiments the late 1960s, but by the end of the 1970s physicists in the US had inferred the existence of a fourth and fifth and finally, in 1995, the sixth, "top", quark. By 2000, the tau neutrino, the last of the leptons to be discovered, had also been bagged. On the other side of the pond, the gluon was snared at the DESY laboratory outside Hamburg, Germany, in 1979; the W and Z bosons in 1983 at CERN. And finally, in 2012, the Higgs boson – the last outstanding particle predicted by the standard model.

For Steven Weinberg of the University at Texas in Austin, another major figure in the development of the standard model, its triumphant march has been something quite special. "To fool around at your desk with mathematical ideas and then find that, after spending a few billion dollars, experimentalists have confirmed them... there really isn't anything comparable to it," he says. So why aren't he and others like him rejoicing?

For many reasons. Some are aesthetic. Why, for example, do particles come in three generations, with the heaviest quark weighing 75,000 times more than the lightest? The standard model's equations might be elegant, but to give them their predictive power, they must be fed more than 20 "free" parameters, such as particle masses, by hand. A truly fundamental theory would use the power of quantum theory, or perhaps some deeper idea that nobody has yet thought of, to prune that thicket.

Then there is the fact that the standard model does not technically unify the strong force. Electroweak theory and quantum chromodynamics are bolted together, rather than mixed up at the level of quantum fields as the weak and electromagnetic forces are – the first hurdle of many on the difficult route towards an ultimate theory of everything. That's before we even talk about gravity, which is described by the distinctly non-quantum general theory of relativity. And while we are not talking about gravity, why is this force so phenomenally weak compared with the others? This "hierarchy problem" is one of the standard model's most puzzling features.

There are also hints from experiments that all is not well. The supposedly massless neutrinos do in fact have a small mass. That blots the standard model's mathematical consistency and is, perhaps, a first pointer to new physics beyond. More mysterious still are dark matter and dark energy, those stuffs that astronomers suggest make up almost 95 per cent of everything out there. The standard model remains silent on their identity.

Faced with such gaping holes, theorists have turned to the solution that has served them so well up till now: plug the gaps with new particles and symmetries. But reality seems to have stopped playing ball. No particle collider has yet delivered more than a hint of anything unexpected and exotic. "There is a real possibility that the LHC will simply go on confirming the standard model," says Weinberg.

What then? In short, we don't know. Without further guidance from the LHC or elsewhere, we could find ourselves in the position of Greek philosopher Democritus when he reasoned that matter couldn't be sliced up indefinitely – an idea only vindicated by experiment over 2000 years later. It is worth remembering that the first "atoms" to meet his description weren't the last word. For all the standard model's successes, we are far from knowing whether Gell-Mann's quarks will be either. ▮

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THE PRINCIPLES OF REALITY

COSMOLOGY

Back in the 1860s, James Clerk Maxwell was melding electricity and magnetism into one unified theory. But however he sliced the equations, they only made sense if light travelled through space at the same constant speed, regardless of the speed of its source.

This is odd. If someone fires a bullet from a moving car, to a bystander the bullet travels at the sum of its speed and the car's speed. Yet when 20 years later US physicists Albert Michelson and Edward Morley were looking for the luminiferous ether, a medium supposed to carry light, they reached the same conclusion: however you look at it, the speed of light is a constant.

Not only that, it is the ultimate cosmic speed limit. No influence – not matter, not information, not gravity or any other force – may travel faster than it. Reports of cosmic speed breakers, such as faster-than-light neutrinos announced in 2011, have always turned out to be wrong. Einstein raised the constant speed of light to a principle of nature, and began to rebuild physics around it – the starting point of his twin theories of relativity.

1 Constant speed of light

Nothing can exceed this cosmic speed limit

Modern fundamental physics consists of two main pillars: the "standard models" of cosmology and particle physics, based on general relativity and quantum theory, respectively. Those theories were both the product of a revolution in our understanding that began in the early 20th century, with the recognition of a few key – perhaps counter-intuitive – principles of nature.

4 Quantisation

Things come in bite-size chunks

PARTICLE PHYSICS

The origin of quantum theory was, quite literally, a light-bulb moment. In 1900, Max Planck was trying to describe mathematically the energy output of light bulbs, and so make better ones. Existing theories failed to match reality. After a few false starts, Planck found he could bridge the gap by making a radical assumption: the electromagnetic energy given out by a radiating body was emitted not continuously, but in indivisible packets.

Planck initially thought these "quanta" were a limitation of the theory, not a description of reality. But in 1905, Einstein showed that the way some metals expel electrons when light shines on them – the photoelectric effect – could also be explained by assuming that light is made of discrete particle-like quanta, which he called photons. This was just the beginning. As quantum theory developed, it became clear that not just energy, but many other properties such as electric charge and spin, come in units of a minimum size. Why that should be, no one knows.

In the 16th century, Galileo noticed that falling objects accelerated at the same rate regardless of their mass. A feather and a hammer dropped from the Leaning Tower of Pisa will hit the ground at the same time, once you discount air resistance. During the Apollo 15 lunar landing, astronaut David Scott confirmed that principle on the airless moon.

Newton showed that this could only be true if an odd coincidence held: inertial mass, which quantifies a body's resistance to acceleration, must always equal gravitational mass, which quantifies a body's response to gravity. There is no obvious reason why this should be so, yet no experiment has ever prised these two quantities apart. As with light's constant speed, it was Einstein who declared this equivalence a principle of nature.

2 The equivalence principle

Gravity and acceleration always look the same

A few decades before Galileo, Copernicus dared to suggest that Earth was not a special place in the cosmos. A century or so later, Newton in his great treatise *Principia* assumed that the solar system was embedded in a uniform space that extended vast distances in all directions.

These are the origins of what in modern cosmology has morphed into the cosmological principle: gaze out into the universe and everything is more or less the same everywhere and in whatever direction you look. Local clumps of matter exist in the form of solar systems, galaxies and clusters of galaxies, but on a big enough scale, everything averages out to uniformity.

It's a simplification that makes the mathematics a lot easier when we're trying to build a working model of the cosmos. But our limited view makes it difficult to say whether it truly is a universally valid principle. The discovery of ever-bigger structures, for example, 2013's whopping 10 billion-light-years-wide arc of galaxies dubbed the Hercules-Corona Borealis Great Wall, is calling that into question.

3 The cosmological principle

The universe is the same in all places and in all directions

5 Uncertainty

There's a limit to how much any of us can know

If you kick a football, knowing where it is doesn't stop you knowing where it's going. Not so with a subatomic particle. The more precisely you know its position, the less precisely you know its momentum, and vice versa.

This is the quantum uncertainty principle, devised by the Werner Heisenberg in the mid-1920s. It connects not just position and momentum, but energy and time and a whole host of other pairs of quantities. Uncertainty doesn't come from the accuracy of our measuring devices: it is apparently a fundamental limit on how much we can know about the world.

Uncertainty shapes our world in unsuspected ways. It allows particles to "tunnel" through otherwise insurmountable energy barriers to initiate nuclear fusion in the sun, for example. It also enables them to pop up out of a seemingly empty vacuum for short periods – an ability that's crucial for explaining how the quantum forces that shape reality operate.

6 Wave-particle duality

Quantum objects exist in many different guises at once

The discovery in the early 20th century that light comes divided into discrete, localised chunks – particles – created a puzzle. Light also interferes with itself, diffracts and otherwise acts as if it is a non-localised wave.

In 1924, Louis de Broglie proposed that this behaviour was universal and worked both ways: if wave-like light can act like a particle, electrons and other matter particles can also act like waves.

In this dual wave-particle picture, a quantum object exists in a wave-like "superposition" of all its possible positions or states, only settling in one state on measurement. Erwin Schrödinger lampooned this idea in his thought experiment about a cat that is simultaneously alive and dead. But experiments since have made single particles as large as buckyballs – molecules made of 60 carbon atoms – diffract and interfere at two slits as if they were a wave, and superposition is one basis of the much-touted, enhanced information-processing power of future quantum computers.

3

2

1

SPECIAL RELATIVITY

As Einstein worked out, the principle of a constant speed of light has some odd consequences. In everyday experience, two cars approaching each other at 100 kilometres an hour would collide at double that, 200 km/h. But imagine you're sitting in one of two spaceships approaching each other, each travelling at 90 per cent of the speed of light, *c*. From the perspective of one, at what speed is the other approaching?

The exact figure doesn't matter* – but it can't be bigger than *c*. In Einstein's special theory of relativity of 1905, time and space warp to accommodate light's speed limit. Moving clocks tick slower and moving rulers appear shorter, so there is no one objective measure of time and space – and you really will age less in a speeding spacecraft. At our normal speeds, these warping effects are negligible, but close to light speed they become hugely significant, and ensure no object can ever cover a given space in a shorter time than light can. (*It's 99.4 per cent of the speed of light.)

$E = mc^2$

This most famous equation of physics stems from special relativity, and says that mass is just a concentrated form of energy, connected by the constant speed of light. So bash particles together at very high energies, as in CERN's Large Hadron Collider, and you can create other, more massive particles – a path of discovery that eventually led to the standard model of particle physics.

GENERAL RELATIVITY

Einstein's warped theory of gravity

If motion warps space and time (see "Special relativity", left), then so does acceleration – and gravity is a form of acceleration. That's the lesson of Einstein's magisterial general theory of relativity of 1916, which combines special relativity and the equivalence principle into our working theory of gravity. Massive objects bend space and time around them, making things seem to accelerate towards them. General relativity provides a framework to explain the large-scale workings of the universe, but a cosmological model requires further information: how matter is distributed.

4

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7 The laws of thermodynamics

The only component of physics to survive the parallel revolutions of general relativity and quantum theory, the laws of thermodynamics were developed in the 19th century to explain how steam engines work. They still determine what processes can and can't occur in the universe on all scales.

The first law of thermodynamics dictates the conservation of energy: energy can be neither created nor destroyed. The second law says that the amount of useful energy will always diminish as a quantity called entropy, equating to the disorder in a system, increases. This unavoidable rule superimposes a direction on physical processes that many physicists see as the origin of the flow of time.

QUANTUM MECHANICS

The theory of subatomic particles and forces

If general relativity is the theory of the universe at large scales, on small scales quantum mechanics calls the shots. Derived from the principles of quantisation, uncertainty and wave-particle duality, it is a peerless predictor of the workings of subatomic particles – although the principles behind it often remain counter-intuitive and mysterious. Like general relativity, quantum mechanics is just a framework. Before it can be applied to the workings of real particles that often move at close to the speed of light, it must be married in some way with special relativity.

THE STANDARD MODEL OF COSMOLOGY

When Einstein first used general relativity to build a cosmic model, he followed the orthodoxy of the day and assumed the universe was static: neither expanding nor contracting. Observations in the 1920s, however, showed that distant galaxies are "redshifted" as if they are moving away from us. Others then used his theory, plus the simplifying cosmological principle that the universe's matter is uniformly distributed, to build models of an expanding universe. This was the beginning of today's standard cosmological model. It describes a universe that began in the hot, dense, infinitesimal pinprick of the big bang some 13.8 billion years ago – and contains a few surprises that we still find hard to explain.

UNIFIED THEORIES OF PHYSICS

The current state of physics is oddly disjointed. The quantum field theories of the electroweak and strong interactions sit in uneasy coalition within the standard model of particle physics, awaiting a "Grand Unified Theory" of both. Meanwhile the failure to marry general relativity and quantum theory mean gravity stands apart from all other forces, and our two standard models do not talk to one another at all.

When subatomic particles interact, gravity is generally so weak that it can safely be ignored. But in some realms, the two must come together: in black holes, for example, or in describing the universe's tiny origins in the big bang. Without a quantum theory of gravity, we face a seemingly impenetrable barrier to ultimate enlightenment about physical reality.

QUANTUM FIELD THEORIES

Mass and energy are interchangeable, so says special relativity. Particles can pop out of nowhere, says quantum theory. Quantum field theory marries those ideas to depict all particles as "excitations" in underlying fields. British physicist Paul Dirac started the ball rolling in the late 1920s with his equation describing how relativistic electrons behave.

The Dirac equation had a sting in its tail: it predicted the existence of a particle identical to the electron in every way, apart from the opposite electric charge. The positron, the first antimatter particle, was duly discovered in cosmic rays a few years later. It was the first of a whole new menagerie of particles that theorists proposed as quantum field theories evolved – and that later popped up in reality.

THE STANDARD MODEL OF PARTICLE PHYSICS

The product of many decades of theoretical work, meticulously confirmed by experiment, the standard model of particle physics covers the workings of three of the four forces of nature. It describes the interactions of force-carrying boson particles with matter-making fermions, and two quantum field theories lie at its heart. Quantum electrodynamics (QED) is the unified "electroweak" theory of electromagnetism and the weak nuclear force. Quantum chromodynamics (QCD) is the theory of the strong nuclear force. The crowning glory of the standard model came in 2012, with the discovery of the Higgs boson, predicted almost five decades earlier. This leaves a theory that is complete – yet also strangely incomplete.

WHY IS THERE SOMETHING RATHER THAN NOTHING?

German philosopher Martin Heidegger called this "the fundamental question of metaphysics". His angst-ridden non-answer was that a fear of nothing was the defining feature of the human condition. Our current theories of physics bring us a little further – but also reveal the same mystery in a different form.

WE CAN attempt to start our attempt to answer why there is something rather than nothing by posing a different, even more metaphysical question: why should we presume that nothing is more likely than something? After all, if we accept that we exist to ask the question, then we've proved that something exists. It's a whole lot harder to prove that nothing can exist.

It's tempting to think that modern physics has made this line of reasoning easier, because it doesn't have a lot of nothing. According to quantum field theory, even the vacuum of space is a lively soup of particles and fields popping up out of nowhere. This kind of random fluctuation is thought to have ultimately created our cosmos of stars, planets and existential worriers out of the quantum vacuum.

And even if there were no quantum vacuum filling it, empty space would be anything but nothing. Old-school physics admits it has at least one property, size – there's pretty much an absolute vacuum betweenEarth and the moon, but that doesn't mean we're right next door. And according to Einstein's relativity, space-time is in some way a physical, malleable object warped by objects with mass and rippled by the passage of gravitational waves.

So within the context of our modern understanding of reality, the answer to why there is something rather than nothing becomes simply: the laws of physics make it more likely that way. That admittedly only gets us so far. "The ballyhoo about a universe popping out of the vacuum is a complete red herring," says physicist Paul Davies of Arizona State University in Tempe. "It just dodges the real issue, which is the prior existence of the laws of physics."

"Even if the answer to why there is something rather than nothing were because of how quantum field theory works, the question would become why are the laws of quantum field theory as they are," says David Deutsch of the University of Oxford.

One answer might be because a universe built on this basis is particularly prone to producing conscious observers who ask what they think are probing questions. A popular idea is that all the other possible laws of physics – including no laws – exist elsewhere in a "multiverse" of all possible worlds.

↓ Turn to page 43 later in this chapter for more on the multiverse

In that case, why a multiverse? In the end, says Deutsch, physicists are going to have to accept they can only ever shift the goalposts on this one. "It's a philosophical question and that's that." He thinks this is actually a good thing. Even if science could reveal an ultimate answer to why stuff is, we shouldn't want it. "We can't have a magic formula that resolves all problems," he says. "That would be a disaster, thinking would become pointless." ▮

GRAFISSIMO/ISTOCKPHOTO

THE MYSTERY OF MATTER

Physicists may be able to get away with dismissing the "why something rather than nothing?" enigma as a philosophical question outside their purview. They have more trouble batting away the related question of why the material universe exists. After all, it is a concrete prediction of their theories that it shouldn't be there.

IF YOU were to list the imperfections of the standard model of particle physics, pretty high up would have to be its prediction that we don't exist.

The culprit is one of the most unexpected apparitions in the theory. In 1928, British physicist Paul Dirac was attempting to marry quantum theory and Albert Einstein's special relativity to describe how the electron worked – the very first effort to devise a relativistic quantum field theory of the sort that came to underlie the standard model. But the elegant equation he devised came with a nasty sting. For every positive-energy solution representing an electron, there was also a negative-energy one, representing… what?

Dirac initially thought the "holes" in this theory might be protons, then the only other subatomic particle known. But it soon became clear this wouldn't wash, and Dirac's theory was in big trouble. A great believer in beauty as a beacon for truth, in 1931 Dirac took the plunge. His equation, he wrote, described "a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti- ›

electron." Dirac had just invented antimatter. It was actually found a year or so later by US experimentalist Carl Anderson, who had no knowledge of Dirac's theory, while investigating the make-up of cosmic rays.

According to quantum field theory, matter and antimatter are both born together and die together. The quantum vacuum of space is in fact filled with pairs of matter and antimatter particles that borrow energy from the vacuum to come fleetingly into existence. Fleetingly, because as soon as they come into contact, they "annihilate" with one another, turning back into energy once more.

This underlying picture is absolutely crucial to the sound working of the standard model – but it means also that the standard model makes a solid prediction that matter and antimatter were created in equal amounts at the big bang. By rights, they should have annihilated each other totally in the first second or so of the universe's existence. The cosmos should be full of energy in the form of light, and little else.

And yet here we are. So too are planets, stars and galaxies; all, as far as we can see, made exclusively out of matter. Reality 1, theory 0.

There are two plausible solutions to this existential mystery. First, there might be some subtle difference in the physics of matter and antimatter that left the early universe with a surplus of matter. It wouldn't have to be much – enough just to allow one matter particle per billion to survive. And in fact the standard model does provide for just such an asymmetry in the workings of the universe. This comes in the form of a process known as CP violation, meaning processes involving antimatter and matter particles work in slightly different ways. The trouble is that the known sources of CP violation within the standard model are not nearly enough even to account for a one in a billion effect.

Experiments such as LHCb at the Large Hadron Collider at CERN near Geneva, Switzerland, are aiming to solve the mystery, perhaps by uncovering evidence of unknown heavier particles that could provide new sources of CP violation. These might also for good measure be candidate particles to make up the universe's missing dark matter.

CERN is also home to the Antimatter Factory, which houses a series of experiments approaching the problem from a different angle. Their aim is to make sufficient quantities of antihydrogen, the simplest possible neutral anti-atom consisting of an anti-electron, or positron, and an antiproton, to test whether its properties differ at all from those of hydrogen. If our current theories are right, they shouldn't at all.

The Antimatter Factory is also aiming to answer the question of whether antimatter falls down under the influence of gravity, like normal matter, or up. If the answer's up, then a rewrite of the theory books is in order. It might also supply a different answer to the question of why matter exists. Gravity is as far as we know only an attractive force, but if matter and antimatter repel each other gravitationally, they could have chased each other way to opposite sides of the cosmos in the instants after the big bang, rather than annihilating. In that case, somewhere out there, in some mirror region of the cosmos beyond our view, antimatter is lurking and has coalesced into anti-stars, anti-galaxies and maybe even anti-life. ▮

WHAT ARE SPACE AND TIME?

The experience of space and time is perhaps the most fundamental feature of reality as we perceive it. But our current theories can't entirely reproduce our experience – and can't even agree among themselves what space and time are.

TO ISAAC NEWTON, space was the "sensorium of God", the organ through which the deity surveyed His creation. It was absolute, unchanging, infinite. Flowing through it "equably without regard to anything external", as Newton wrote in his great physical treatise *Principia*, was another similarly absolute heavenly creation: time.

Not everyone bought that idea. Newton's perennial antagonist Gottfried Leibniz was notably sniffy of a God who needed an organ to perceive things, and asked pointedly whether a clockmaker deity would need to "wind up his watch from time to time". A few centuries on, God features less prominently in the debate, but arguments about the nature of space and time swirl on. Are both basic constituents of reality, or neither – or does one perhaps emerge from the other in some way?

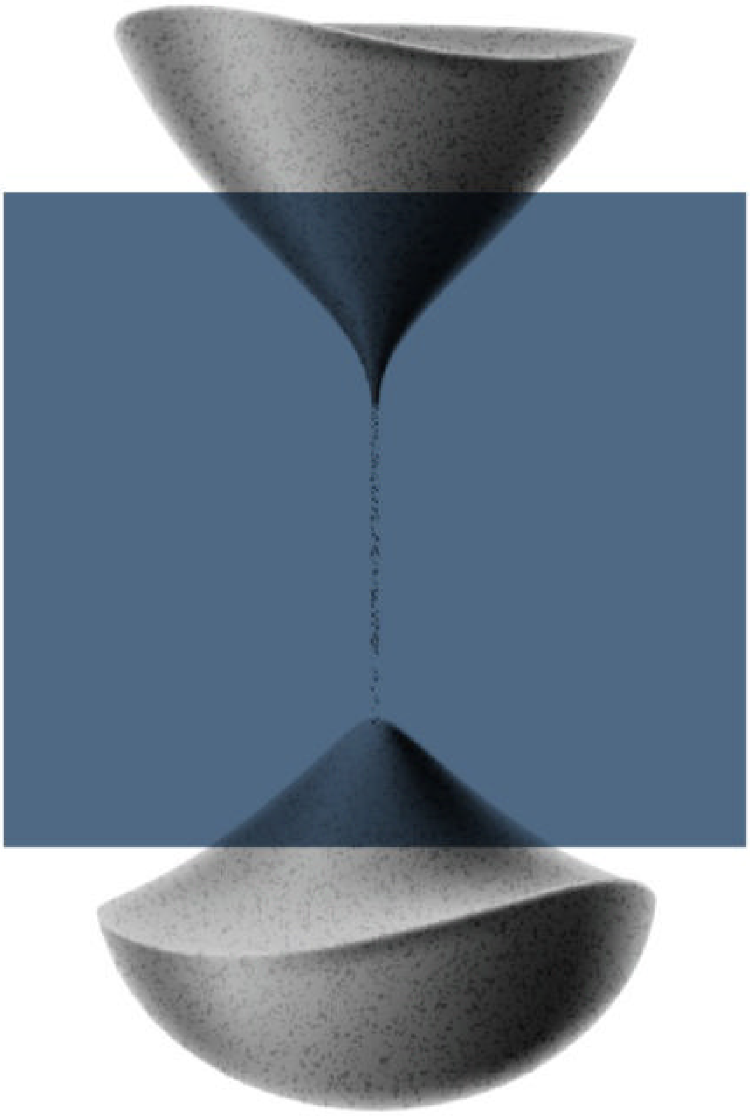
These questions go to the heart of what physics is about. "When we find the simplest equations for everything in the universe, the fundamental quantities would be what appear in those equations," says theorist Joe Polchinski of the University of California, Santa Barbara. That makes it all the more embarrassing that general relativity and quantum theory differ so radically in how they deal with space and time.

When Einstein developed his special theory of relativity in 1905, it undid Newton's clockwork universe, in which objects in an absolute space followed the beat of a heavenly timepiece. Space and time are intertwined into one four-dimensional fabric on which events play out, called space-time. People moving at different speeds measure space-time differently. Just as "here" does not mean the same thing to people in different places, so it is with "now" in Einstein's relativistic space-time.

General relativity, which came along in 1916, muddied the waters still further: massive objects curve space-time, and measurements of ruler lengths and clock ticks depend on the strength of the prevailing gravitational field. In this picture, absolute time is an illusion brought about by an accident of circumstance: we live our whole lives in roughly the same gravitational field and at roughly the same low speeds.

In quantum mechanics, things are even more ›

PIXEL PARTICLE/ISTOCKPHOTO



IRINABELOKRYLOVA/CSA-ARCHIVE/ISTOCKPHOTO

abstruse. Time is not part of the abstract space, known as Hilbert space, in which the wave function that describes a quantum object's state operates, but sits outside it. When we measure the evolution of the quantum world, it is to the beat of an external timepiece of unknown provenance – rather like Newton's picture. The status of space, meanwhile, depends on what you are measuring. The wave function of an electron orbiting the atomic nucleus includes properties of physical space such as the electron's distance from the nucleus. But the wave function describing the quantum spin of an isolated electron has no mention of space. According to the mathematics, the picture often painted of an electron physically rotating is meaningless.

It gets worse. A key feature of our experience of reality is that while we can (local obstacles and the pull of gravity excepted) move in all directions, we can only move forwards in time. It's as if we are carried in the coracle of an eternal present down an inexorable stream of time from past to future.

But physics says "no" to time's flow. Quantum theory indicates that things should work just as well backwards as forwards. Meanwhile, relativity's difficulty putting events in any one unambiguous order leads physicists to suggest that reality is a static four-dimensional block of space-time, in which all of time exists all at once.

It's unclear how we might resolve this clash on the nature of space and time both between our two great theories of reality and between them and our own perceptions. On the first point, the hopes many physicists rest on developing a quantum theory of gravity that might unite quantum theory and general relativity. But such theories are far away, and they produce puzzling problems of their own – string theory, still the most favoured flavour of such a theory, for example, requires the existence of extra dimensions of space far too small for us to see.

As for the flow of time, most physicists attempt to explain that away by appealing to the ineluctable rise of entropy. Entropy is a measure of disorder, and according to the second law of thermodynamics, as mysteriously cast-iron a law as we know of, entropy always increases: ice creams always melt, eggs break but don't de-break, socks get lost in the wash but never found. On a cosmic scale, we explain away flowing time by saying the universe must have started in an implausibly ordered configuration, and what we experience as time is the constant drift away from this state. The mystery of time just comes the different mystery of the universe's initial conditions.

So while things may be flowing in the block universe, time isn't. "Time is the direction on that block in which physics tells its most compact, powerful narrative," says philosopher of science Craig Callender at the University of California, San Diego. Reality as we are experiencing it "now" is like the page of a book. "You turn pages in the direction the laws evolve," says Callender. ▮

INTO THE MULTIVERSE

Whether we are searching the cosmos or probing the subatomic realm, our most successful theories can lead to the conclusion that our universe is just a speck in a vast sea of universes – a multiverse. Until recently, many physicists were reluctant to accept the idea. Advances in cosmology, quantum mechanics and string theory have brought a change of heart. And it seems there isn't just one type of multiverse, but many.

THE idea of the multiverse goes back to the early 1980s, when physicists realised that the big bang created an equally big problem. When astronomers measured its afterglow, radiation known as the cosmic microwave background (CMB), they found that it was unfathomably uniform – even at opposite ends of the visible universe. Finding a temperature match between such widely separated regions to within 1/10,000th of a degree, as we now know it to be, was as surprising as it would be to find that their inhabitants, if any, spoke the same language.

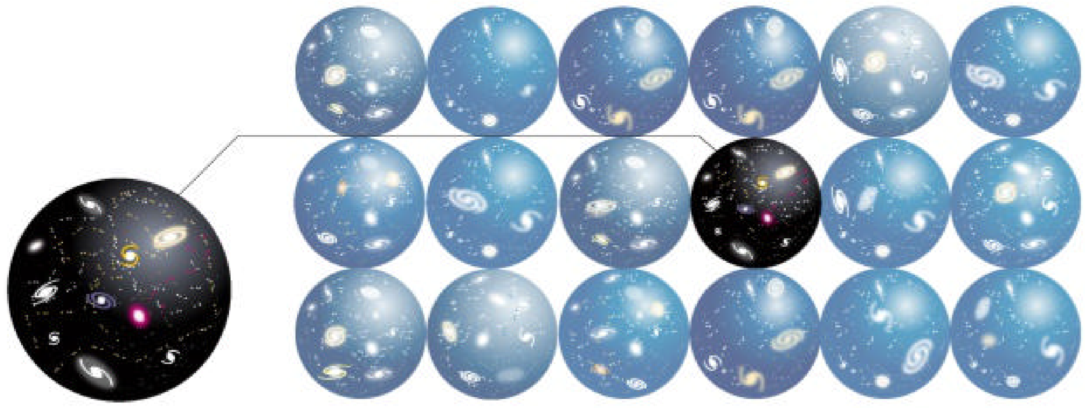
The problem was solved brilliantly by cosmologists Alan Guth and Andrei Linde, among others, with the idea of a period of breakneck expansion of space-time at the beginning of the universe. This inflation accounts for the uniform temperature of the CMB and resolves another conundrum: why space appears flat, like a three-dimensional version of an infinite table top. Inflation has become an incredibly successful theory, precisely predicting the subtle ripples since measured in the CMB, which are echoes of quantum perturbations thought to have seeded galaxies and stars.

Guth and Linde's attempt to explain our universe also led directly to a multiverse. That's because inflation didn't conveniently stop at the farthest regions from which light can travel to us today. Depending on how inflation unfolded, the universe could be 10^{10} times, 10^{20} times, or even infinitely larger than the region we see. Inflation implies an expansion faster than the speed of light, meaning that beyond the horizon of our observable universe lie other parts of the universe that are effectively separated from ours. No influence can travel between these regions, essentially creating an infinite number of other worlds.

What would they look like? Max Tegmark, a cosmologist at the Massachusetts Institute of ›

THE MULTIVERSE HIERARCHY: LEVEL 1

If the big bang started with a period of inflationary growth, there would be a multitude of universes a lot like ours – but with different arrangements of matter



PHYSICS:
Like ours, but with all possible initial conditions and histories replicated an infinite number of times

SUPPORT:
Plays to the idea of the principle of mediocrity– that there's nothing special about the universe we see

RELATIONSHIPS:
All level 1 universes bear a family resemblance to ours and to each other

OUR UNIVERSE
42 billion light years across – the distance light has travelled in our expanding universe

CONNECTIONS:
Since everything that can happen in our universe has happened in some other level 1 universe, there may be a direct connection between level 1 and level 3 quantum multiverses

Technology, points out that although inflation predicts an abundance of universes, they all feature the same particles, forces and physical laws we find in our cosmic patch. But while, in our universe, elementary particles come together to make stars and galaxies in a particular way, the universe next door will contain a different arrangement of stars and galaxies, and so will our neighbours' neighbours. Still, Tegmark has shown that even if a universe like ours were completely filled with elementary particles, they can only be arranged in a finite number of ways. It's a huge number, 2 to the power of 10^{118}, but since there's no sign that space is finite, there's room for every arrangement to repeat.

This means that if you travel far enough, you will eventually encounter a universe containing an identical copy of you. Tegmark has calculated that your nearest copy lives about 10 to the power of 10^{29} metres away. Carry on and you will find our universe's twin lies 10 to the power of 10^{118} metres from here. Since an infinite universe hosts an infinite number of variations, somewhere you have just won the Olympic 100 metres.

Abundant as these universes are, there is nothing exotic about them. Tegmark classes the universes implied by simple inflation or an infinite expanse of space as the first level of a four-tier hierarchy that gets much, much stranger.

Take the second type of multiverse. Soon after inflation was discovered, Linde realised that it could be an ongoing or eternal process. When the enormous energy of empty space creates an inflating baby universe, the space around it, still crackling with energy, continues to expand even faster. That space could then sprout more universes that themselves inflate, and so on and on. "Practically all models of inflation that have been discussed predict eternal inflation," says Alexander Vilenkin at Tufts University in Boston, who pioneered the idea in the 1980s. Guth dubs it the ultimate free lunch.

The eternal-inflation smorgasbord includes an infinite number of level 1 universes, but many other varieties as well. Each universe turns out in a different way, so features once thought universal, such as the masses of elementary particles and the strength of fundamental forces, differ. The bubble universes from eternal inflation include every permutation the laws of physics allow, leading Linde to quip that it's not just a free lunch but "the only one at which all possible dishes are available".

Those universes are part of the second level of Tegmark's multiverse hierarchy. It also includes some 10^{500} sorts of universe implied by string theory, the leading contender for a "theory of everything" that would explain all the particles and forces of nature.

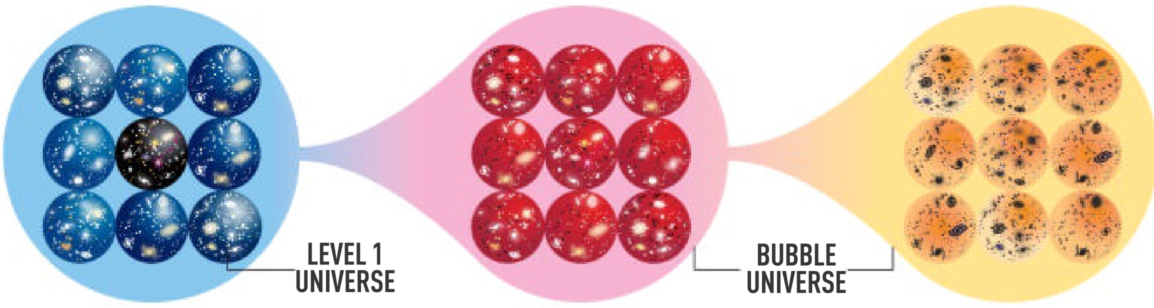
↓
Proceed to page 48 for more on theories of everything

Today's standard model of particle physics includes a score of parameters whose values physicists can measure but can't explain, such as the mass of an electron. String theorists hoped their theory would explain why those parameters have the values they do, and so why our universe is the way it is.

They were sorely disappointed. Rather than producing

THE MULTIVERSE HIERARCHY: LEVEL 2

In the theory of eternal inflation, the space between universes continues to expand, and a limitless number of new "bubble" universes, with very different properties, continue to form. Each bubble universe contains an infinite number of its own level 1 universes



PHYSICS:
Other bubble universes exhibit different laws of physics and have different dimensionality, particles, constants and forces to those seen in our universe. We might eventually discover that all these parameters flow from the same "theory of everything"

SUPPORT:
Inflation explains the uniformity and flatness of our universe and details of the cosmic microwave background. Eternal inflation implies bubble universes and provides a way of supplying string theory with the many universes it demands

RELATIONSHIPS:
Level 2 universes vary greatly. They represent separate bubbles or domains with different properties, and are separated from each other by inflating space

CONNECTIONS:
Level 2 includes all possible level 1 universes plus an enormous variety of much stranger universes. Since everything that can happen in a particular level 2 universe has happened in other universes, level 2 may also correspond to the universes in the level 3 quantum multiverse

one perfect snowflake – the particles, forces and interactions underpinning our universe – string theory loosed an avalanche of universes, a daunting expanse that Leonard Susskind, a theoretical physicist at Stanford University, dubbed the string theory landscape.

What sets these universes apart is the nature of their space-time. In string theory, nature's particles and forces come about from vibrations of tiny strings in 10 or more dimensions. The reason we only experience four dimensions is because the rest are "compactified" or knotted into intricate structures too small for us to experience. The physics that plays out in any given universe depends on how many dimensions are scrunched up, and their structure. Researchers have identified an enormous number of possible shapes that interact with string-theory fields to define a vast number of universes, most with unfamiliar physical laws and radically different forces and particles.

Eternal inflation provided a convincing mechanism for populating every point in the string theory landscape with an infinite number of real universes. "Originally, string theorists did not like the idea of the multiverse and wanted to have just one solution, but instead they found 10^{500}," says Linde. "Now we must learn how to live in a universe which offers us an enormous multitude of choices."

Finding out why our universe is as it is, when there is such a vast number of alternatives, remains one of cosmology's biggest challenges. Our universe seems inexplicably finely tuned to produce the conditions necessary for life. If gravity were a bit stronger, the big bang would have been a squib. A bit weaker and it couldn't have made galaxies and stars. If the electron's charge differed by a few per cent, stars could not have created the heavy elements that make Earth-like planets. If the strong force varied by half a per cent, carbon wouldn't exist, so neither would life as we know it. Topping the fine-tuning list is our universe's small cosmological constant – the tiny dose of dark energy that is the source of the accelerating expansion of the universe.

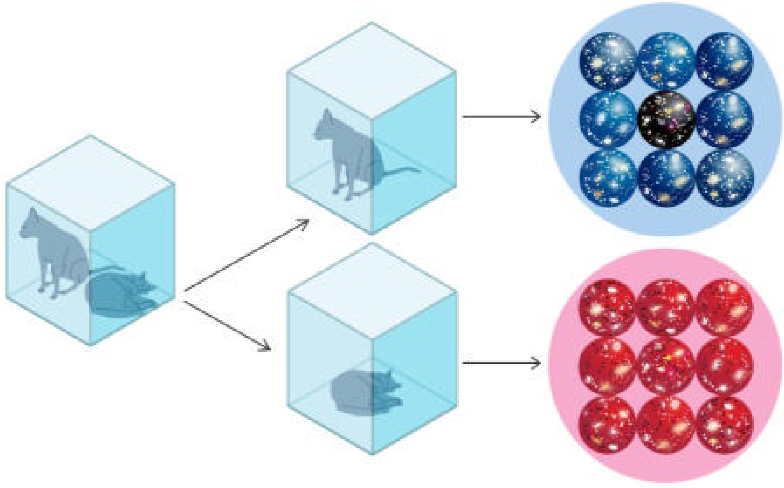
The discovery in the late 1990s that the universe's expansion is accelerating shocked most cosmologists. Quantum theory predicts a level of dark energy roughly 10^{120} times larger than what was found. Since that would blast the universe apart, most researchers had assumed that some undiscovered symmetry would cancel that huge number, leaving a cosmological constant of zero. Nobody predicted that it would not bezero – except one person.

A decade earlier, Steven Weinberg at the University of Texas, Austin, had predicted a small positive cosmological constant. That coup came from applying anthropic reasoning to the multiverse, an approach that is still hotly contested. Weinberg reasoned that for a universe to generate galaxies – and so stars, planets and observers – the amount of dark energy had to fall within a certain range for us to be here to measure it. This amounts to homing in on a subset of universes within the multiverse that have those properties. This probabilistic approach allowed Weinberg to predict the value of the cosmological constant with remarkable accuracy.

"The discovery of the cosmological constant was one of the most unexpected discoveries of the last century, and it was predicted by the multiverse," ›

THE MULTIVERSE HIERARCHY: LEVEL 3

The many-worlds interpretation of quantum mechanics suggests a continually branching series of multiverses



PHYSICS:
Quantum mechanics underlies all level 1 and 2 universes, but arguably with all possible virtual or parallel worlds also realised somewhere in space

SUPPORT:
Quantum mechanics, including ideas of superposed states and collapsing wave functions, is one of the most thoroughly tested and successful theories in physics

RELATIONSHIPS:
Within a given universe, parallel or branching worlds follow the same physical laws. However, once histories diverge, they can no longer interact

CONNECTIONS:
The parallel universes of level 3 may be realised in the multiverses of level 1 and 2

says Vilenkin. "So it's indirect evidence that we are living in a multiverse."

Since then, other researchers have used anthropic reasoning to constrain the amount of dark energy, the ratio of dark matter to ordinary matter, and the mass of elementary particles such as neutrinos and quarks. Using anthropic reasoning to winnow out our kind of universe from the multiverse, it seemed, might explain that mysterious fine-tuning. It might, in fact, be the only way. "If the laws and physical constants are different in other places," says Martin Rees, an astronomer at the University of Cambridge, "there's no avoiding it."

Unfortunately, there's a catch in using this approach to elucidate our universe's place in the multiverse: the usual rules of probability may not apply, making it impossible to estimate the likelihood of universes like ours. "You have infinitely many places where you win the lottery, and infinitely many where you don't. So what's your basis for saying that winning the lottery is unlikely?" says Raphael Bousso, a theoretical physicist at the University of California, Berkeley. "It pulls the rug out from under us to prove a theory right or wrong."

This "measure problem" is one of many difficulties we have in understanding cosmological multiverses, but another two levels of Tegmark's hierarchy remain. Level 3 has its origins in quantum theory. Physicists accept that quantum mechanics works brilliantly. It can be used, for example, to calculate a value for the magnetic moment of the electron which matches measurements to 1 part in a billion. However, they have yet to agree on what it means. In the quantum realm, particles don't exist as discrete entities that you can pin down, but as "probability waves". It's the evolution of those waves that lets quantum physicists predict how electrons cloak an atom, how quarks and gluons interact, and even how objects as large as buckyballs can interfere like light waves.

→ See chapter 4 for more on quantum reality

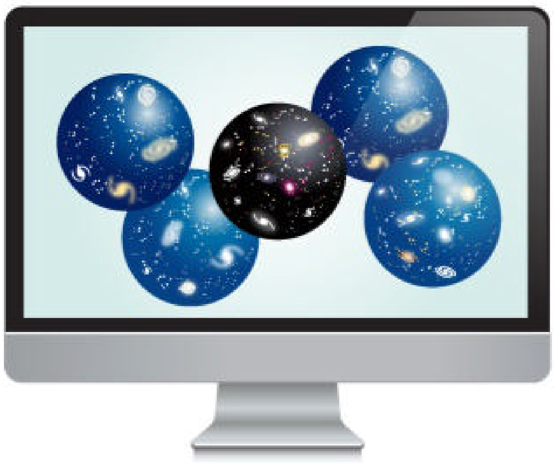
The pivotal question is what happens to an object's probability wave – its wave function – when someone measures it. Niels Bohr, a founder of quantum mechanics, declared that observing the wave function caused it to collapse and a particle to appear at a particular time and place. That, he said, explains why we see just one outcome out of the infinite possibilities embodied in the wave function.

Yet Bohr's interpretation has long been criticised because it suggests that nothing becomes a reality until someone observes it. In the 1950s, such arguments led Hugh Everett, then a graduate student at Princeton University, to explore what would happen if he jettisoned Bohr's argument. When Everett pictured the wave function rolling majestically on, as the maths of quantum theory said it did, he arrived at a still astonishing and controversial conclusion. Known as the many-worlds interpretation, it calls for the existence of a vast swarm of universes paralleling ours, in which all the possibilities can play out.

How real are those parallel worlds? As real as dinosaurs, says David Deutsch at the University of Oxford. "We've only ever seen fossils, and dinosaurs

THE MULTIVERSE HIERARCHY: LEVEL 4

If our universe is just a simulation, there could be infinitely many kinds of universes that differ in arbitrary ways from ours



PHYSICS:
Anythnig goes

SUPPORT:
None. The idea is that long-lived technological civilisations will probably command vast computing power and may choose to run multiple "ancestor simulations" which will soon outnumber natural universes. There may be a one-to-one relationship between mathematics and reality: every conceivable mathematical system may represent a real universe

RELATIONSHIPS:
Arbitrary or non-existent

CONNECTIONS:
Level 4 must contain the ultimate theory of everything. If so, there's no level 5

dinosaurs are the only rational explanation for them," he says. "Many worlds is the only rational explanation for the quantum phenomena we see. I think this is as good as dinosaurs."

The parallel worlds of quantum theory and the multiple universes created by eternal inflation couldn't seem more different. However, theorists have started to explore the idea that the quantum landscape and the inflationary landscape are one and the same. Bousso and Susskind argue that they produce the same collection of parallel universes. "We both thought for a long time that the multiverse idea and the many-worlds idea were redundant descriptions of the same thing," Susskind says. In 2011, though, he and Bousso developed a consistent way of applying quantum rules to the multiverse. The inflationary multiverse, they conclude, is simply the collection of all the bubble universes that quantum mechanics allows. "The virtual realities of quantum mechanics become genuine realities in the multiverse," Susskind says.

Tegmark also equates the infinite variants of our universe in the level 1 multiverse to the infinity of quantum worlds. "The only difference between level 1 and level 3," he says, "is where your doppelgängers reside."

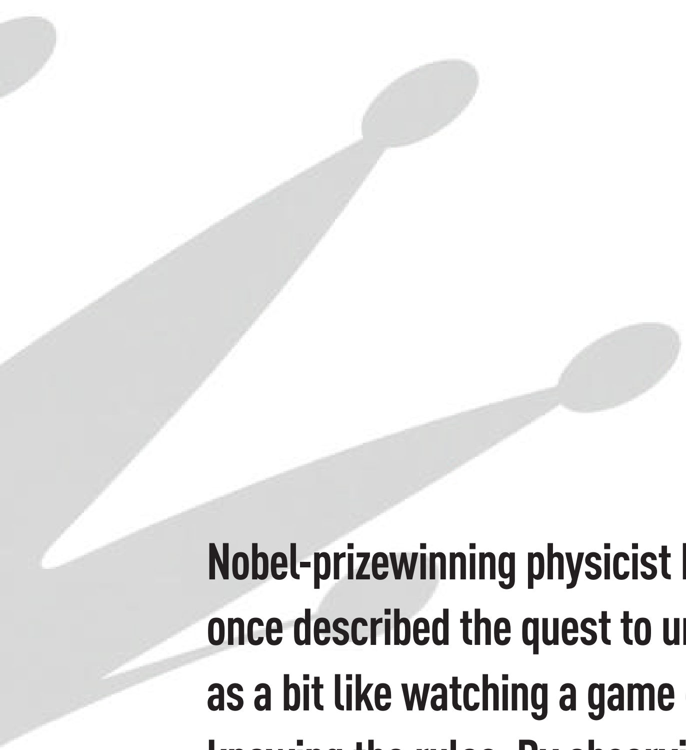
The multiverses mentioned so far demote our universe to the status of a pebble in a vast landscape, but at least they allow it to be real. Philosopher Nick Bostrom at the University of Oxford ups the ante by arguing that the universe we experience is just a simulation running on an advanced civilisation's supercomputer.

→ Turn to chapter 6 for more on Nick Bostrom's argument that reality is a simulation

His argument is simple. Civilisations that last will develop essentially unlimited computing power. Some of those will run "ancestor simulations", reconstructions of their forebears or other beings. Just as millions of us play video games like *The Sims*, a trans-human civilisation would probably run multiple simulations, making it plausible that we are in one of them. Bostrom doubts that we will find evidence that we do or don't live in a simulation. He argues that an advanced civilisation smart enough to create a simulation in the first place would prevent people inside from noticing a problem, or erase the evidence. Tegmark categorises this and several even more speculative forays as level 4 multiverses.

Three decades after the concept was born, many researchers now agree that at least some kinds of multiverse stand on firm theoretical foundations, yield predictions that astronomers and particle physicists can test, and help explain why our universe is the way it is. Still, Bousso says, multiverses exist at the frontier of science. "You never know anything for sure when you're working on the edge of knowledge," he says. "But if I didn't think it was by far the best bet, I wouldn't waste my time on it." Susskind agrees, but adds: "We're nowhere near the end of questions. Surprises will happen." ∎

CAN WE FIND BETTER THEORIES OF REALITY?



Nobel-prizewinning physicist Richard Feynman once described the quest to understand reality as a bit like watching a game of chess without knowing the rules. By observing the game, we slowly get to grips with what the pieces are and how they are allowed to move and interact. With the developments of the past century, we've identified many of the pieces and their moves – but we're still far from completing the rulebook.

THE standard model of particle physics arguably fulfils at least one philosophical definition of reality: what exists and what does it do? Yet we know it is nowhere near a complete answer. Just the fact that it leaves out the substances that seem to make up 95 per cent of material reality, dark matter and dark energy, tells us that.

Despite high hopes that the Large Hadron Collider would follow the discovery of the Higgs boson with at least some hints about a more complete theory, none has yet been forthcoming. Meanwhile the fact that the standard model, rooted in a picture of quantum particles and fields, describes three of four fundamental forces we know of in nature – but not the fourth – remains a fundamental mystery.

Gravity remains out on a limb, described by Einstein's resolutely classical theory of general relativity. These two theories don't play by the same rules. If one is chess, the other is backgammon. Quantum theory is predicated on reality existing in tiny, indivisible chunks, relativity on it being smooth and continuous. That means we are fated not to understand situations where both gravity and quantum theory are in play, such as in black holes, the big bang, or tiny particles in gravitational fields.

The most pressing challenge for the study of physical reality today, then, is to find a way of unifying quantum theory and relativity in one game. "Each of these pieces is contradicted by the other," says Carlo Rovelli at Aix-Marseille University in France. "So what's needed is more than sticking the pieces together. We are searching for a coherent way of thinking in light of what we know."

There are options on the table, not least one Rovelli has pioneered, loop quantum gravity, which holds that space-time isn't smooth but made of tiny loops. There is also the old stalwart, string theory, which says all particles and forces are points on one-dimensional strings that extend through seven or more invisible extra dimensions. Both loop quantum gravity and string theory purport to solve some of the incompatibilities between explanations of gravity and quantum effects, but both also have their problems. As we've seen, string theory spawns inexplicable multiverses and also the "holographic principle", which holds that three-dimensional space is actually a kind of projection onto a two-dimensional surface.

A more recent avenue being explored by theoretical physicists is quantum entanglement, the phenomenon whereby two particles can influence one another even when they are separated by huge distances. This approach has recently shown that entanglement can define the geometry of space: the stronger the entanglement, the more warped space is. Some physicists suggest this means that space-time emerges from quantum mechanics. In this case, quantum theory is the more fundamental description of reality, and should be where we find answers to ›

ALTAYB/ISTOCKPHOTO

the questions of what exists and what it does.

A successful unification of quantum theory and relativity would still be glaringly incomplete, however, unless it also straightens out that other must-have feature of reality already mentioned, time. A possible way to work around the fundamental differences in the way the two theories treat time might be to propose that time isn't a fundamental ingredient of reality at all, but what physicists call an emergent phenomenon.

One way to think about this is to imagine warming your hands by a fire. Energetic molecules in the air are bouncing against your skin, warming it up. But we don't need to explain what's happening in terms of the particles: a rise in temperature adequately captures the phenomenon. Temperature is a perfectly good way of thinking about an aspect of reality as long as we don't assume that it is a fundamental thing.

↑ Turn back to page 41 for more on the nature of time

This way of thinking may even lead to an entirely different perspective on reality, indicating that the traditional reductionist approach of science, of drilling down ever deeper to seek even more fundamental layers, has hit a limit. Some physicists say we need to stop fixating on the elusive "true" nature of reality and focus on building a set of models that describe the various physical phenomena we observe.

One seldom considered question, however, is how exactly models ought to seek to explain reality. Some, such as general relativity, take some known quantities about nature – the position of a planet, say – and predict what will happen next. Quantum theory takes a different philosophical approach, assigning probabilities to future outcomes we might see.

→ Read on to the next chapter for more on quantum reality

But these aren't the only methods of explaining reality. Consider a much older branch of physics: thermodynamics, the science of heat, work and power. It doesn't seek to describe the fundamental nature of things, but instead rules what can and cannot happen. For example, it tells us that a scrambled egg cannot be unscrambled and that energy cannot be created or destroyed.

Some physicists are now exploring whether a similar approach can help us make headway. One possibility called constructor theory, developed by David Deutsch at the University of Oxford and his colleagues, starts from the idea that the essence of reality is information, and then sets out what kinds of things are possible and impossible. It is early days, but it has already made predictions in circumstances that defeat other theories, such as the behaviour of quantum particles in a gravitational field.

Where does that leave us? Our understanding of the game is in a state of flux, but we are making progress, even if it isn't exactly what we hoped for. "If the question is, do we have a chance to see the next clear level of understanding, then, yeah, I think we can get it," says Rovelli. Even this is unlikely to be the last word, however. Rovelli thinks it will just reveal more holes in our understanding. "If you want a theory of everything where it all fits, I see no hint that we're close – zero," he says.

It isn't even clear that our brains are actually capable of comprehending reality. Chimpanzees are intelligent but could never grasp quantum theory, or see why it is necessary. Similarly, there may be some fundamental limit to human cognition that prevents us from getting the big picture – though maybe superintelligent machines could one day do so.

From a human perspective, a more fundamental description of reality only promises to shift the true nature of reality yet further from our everyday experiences of it – quite a feat, given the extent to which quantum theory and relativity have already done so. "When I wake up in the morning, for sure, that's my reality," says Claudia de Rham of Imperial College London. "But there is definitely something more fundamental that I will never be able to experience." ▮

→ See chapter 5 for more on perception and reality

CHAPTER 4

THE QUANTUM WORLD

Nothing seems more real than the world of everyday objects – of matter. Our efforts to understand the nature of material reality stretch back millennia, but our best picture of it today is underpinned by quantum theory.

And what a strange picture it reveals. Drill down to the bottommost level, and the world of cast-iron certainty, of material properties that stay as they are and of causes definitely leading to effects, begins to dissolve. It is replaced by a view that is fuzzy and probabilistic, and strangely dependent on how we choose to look at it.

Quantum experiments have revealed enormous holes is our intuitive understanding of physical reality. Trying to explain what goes on leads to some very peculiar and often surprising theories of the world around us, and to a very fundamental question: is matter as we perceive it real? Philosopher Jan Westerhoff kicks off our investigations.

PROFILE
JAN WESTERHOFF

Jan Westerhoff is professor of Buddhist philosophy at the University of Oxford, UK. He has written extensively on metaphysics and the philosophy of mathematics, and is the author of *Reality: A very short introduction*

TAKE an ordinary desk lamp, a few pieces of cardboard with holes of decreasing sizes, and some sort of projection screen such as a white wall. If you put a piece of cardboard between the lamp and the wall, you will see a bright patch where the light passes through the hole in the cardboard. If you now replace the cardboard with pieces containing smaller and smaller holes, the patch too will diminish in size. Once we get below a certain size, however, the pattern on the wall changes from a small dot to a series of concentric dark and light rings, rather like an archery target. This is the Airy pattern – a characteristic sign of a wave being forced through a hole.

In itself, this is not very surprising. After all, we know that light is a wave, so it should display wave-like behaviour.

But now we change the set-up of the experiment a bit. Instead of a lamp, we use a device that shoots out electrons, like that found in old-fashioned TV sets; instead of the wall, we use a plate of glass coated with a phosphor that lights up when an electron strikes it. We can therefore use this screen to track the places where the electrons hit. The results are similar: with sufficiently small holes we get an Airy pattern.

This now seems peculiar. Electrons are particles located at precise points and cannot be split. Yet they are behaving like waves that can smear out across space, are divisible, and merge into one another when they meet.

Perhaps it is not that strange after all, though. Water consists of molecules, yet it behaves like a wave. The Airy pattern may just emerge when enough particles come together, whether they are water molecules or electrons. ›

ANXO VIZCAÍNO

A simple variant of the experiments shows, however, that this cannot be right. Suppose we reduce the output of the electron gun to one particle each minute. The Airy pattern is gone, and all we see is a small flash every minute. Let's leave this set-up to run for a while, recording each small flash as it occurs. Afterwards, we map the locations of all the thousands of flashes.

Surprisingly, we do not end up with a random arrangement of dots, but with the Airy pattern again. This result is extremely strange. No individual electron can know where all the earlier and later electrons are going to hit, so they cannot communicate with each other to create the bullseye pattern. Rather, each electron must have travelled like a wave through the hole to produce the characteristic pattern, then changed back into a particle to produce the point on the screen. This is the famous wave-particle duality of quantum mechanics.

This strange behaviour is shared by electrons, photons and other elementary particles, as well as the protons and neutrons of the atomic nucleus, and atoms themselves. Similar effects have been observed for objects that are large enough in principle to be seen under a microscope, such as buckyballs, molecules made up of 60 atoms of carbon.

In order to explain the peculiar behaviour of such objects, physicists describe them using a mathematical entity known as a wave function, evolving according to a wave equation first written down by the pioneering quantum physicist Erwin Schrödinger in 1926. Despite the fact that these waves have the usual properties of more familiar waves such as sound or water waves, including amplitude (how far up or down it deviates from the rest state), phase (at what point in a cycle the wave is), and interference (so that "up" and "down" phases of waves meeting each other cancel out), what they are waves in is not at all transparent. Einstein aptly spoke of a "phantom field" as their medium.

↓
Are quantum wave functions themselves real?
See page 60 later in this chapter

For a wave in an ordinary medium such as water, we can calculate its energy at any one point by taking the square of its amplitude. Wave functions, however, carry no energy. Instead, the square of their amplitude at any given point gives us the probability of observing the particle if a detector such as the phosphor-coated screen is placed there.

Clearly, the point where an object switches from being a probability wave, with its potential existence smeared out across space, and becomes an actual, spatially localised object is crucially important to understanding whether matter is real. What exactly happens when the wave function collapses – when among the countless possibilities where the particle could be at any moment, one is chosen, while all the others are rejected?

First of all, we have to ask ourselves when this choice is made. In the example described above, it seems to happen just before the flash on the phosphor screen. At this moment, a measurement of the electron's position was made by a piece of phosphor glowing as the particle struck it, so there must have been an electron there, and not just a probability wave.

But assume we cannot be in the lab to observe the experiment, so we point a camera at the phosphor screen and have the result sent via a satellite link to a computer on our desktop. In this case, the flash of light emitted from the phosphor screen has to travel to the camera recording it, and the process is repeated: like the electrons, light also travels as a wave and arrives as a particle. What reason is there to believe that the switch from probability wave to particle actually occurred on the phosphor screen, and not in the camera?

At first, it seemed as if the phosphor screen was the measuring instrument, and the electron was the thing being measured. But now the measuring device is the camera and the phosphor screen is part of what is measured. Given that any physical object transmitting the measurement we can add on to this sequence – the camera, the computer, our eyes, our brain – is made up of particles with the same properties as the electron, how can we determine any particular step at which to place the cut between what is measured and what is doing the measuring?

This ever-expanding chain is called the von Neumann chain, after the physicist and mathematician John von Neumann. One of his Princeton University colleagues, Eugene Wigner, made a suggestion as to where to make the cut. As we follow the von Neumann chain upwards, the first entity we encounter that is not made up in any straightforward fashion out of pieces of matter is the consciousness of the observer. We might therefore want to say that when consciousness enters the picture, the wave function collapses and the probability wave turns into a particle.

The idea that consciousness brings everyday reality into existence is, of course, deeply strange; perhaps it is little wonder that it is a minority viewpoint.

There are other ways of interpreting the quantum measurement problem that do not involve consciousness – though they have peculiar ramifications of their own. For now, let's explore Wigner's idea in more depth.

↓ Find more interpretations of quantum reality on page 67

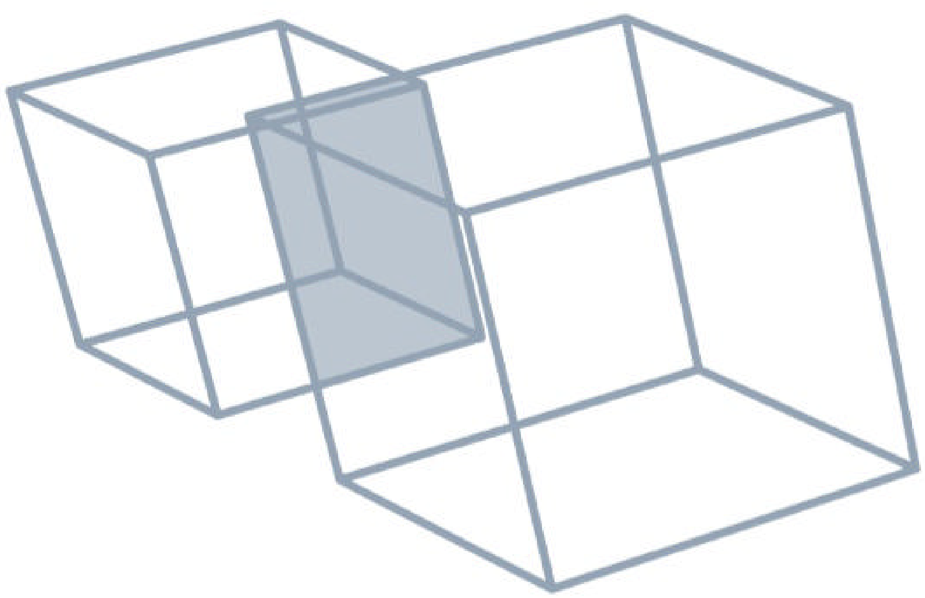
If a conscious observer does not collapse the wave function, curious consequences follow. As more and more objects get sucked into the vortex of von Neumann's chain by changing from being a measuring instrument to being part of what is measured, the "spread-out" structure of the probability wave becomes a property of these objects too. The "superposed" nature of the electron – its ability to be in various places at once – now also affects the measuring instruments.

It has been verified experimentally that objects large enough to be seen under a microscope, such as a 60-micrometre-long metal strip, can exhibit such superposition behaviour. Of course, we can't look through a microscope and see the metal strip being in two places at once, as this would immediately collapse the wave function. Yet it is clear that the indeterminacy we found at the atomic level can spread to the macro level.

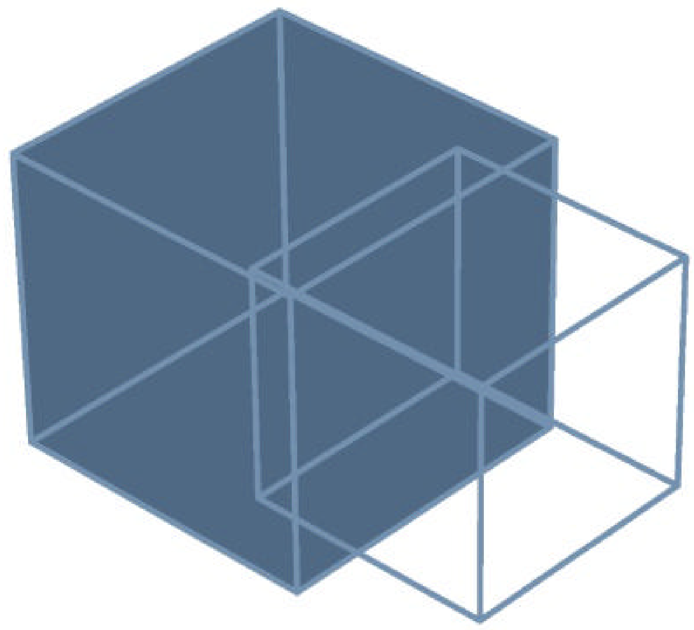
Yet if we accept that the wave function must collapse as soon as consciousness enters the measurement, the consequences are even more curious. If we decide to break off the chain at this point, it follows that, according to one of our definitions of reality, matter cannot be regarded as real. If consciousness is required to turn ghostly probability waves into things that are more or less like the objects we meet in everyday life, how can we say that matter is what would be there anyway, whether or not human minds were around?

→ Turn to page 84 for more on the role of consciousness in creating reality

But perhaps this is a bit too hasty. Even if we agree with the idea that consciousness is required to break the chain, all that follows is that the dynamic attributes of matter such as position, momentum and spin orientation are mind-dependent. It does not follow ›



"Would matter be there if human minds weren't?"



that its static attributes, including mass and charge, are dependent on in this. The static attributes are there whether we look or not.

Nevertheless, we have to ask ourselves whether redefining matter as "a set of static attributes" preserves enough of its content to allow us to regard matter as real. In a world without minds, there would still be attributes such as mass and charge, but things would not be at any particular location or travel in any particular direction. Such a world has virtually nothing in common with the world as it appears to us. The pioneering quantum physicist Werner Heisenberg observed that: "the ontology of materialism rested upon the illusion that the kind of existence, the direct 'actuality' of the world around us, can be extrapolated into the atomic range. This extrapolation, however, is impossible... Atoms are not things."

It seems that the best we are going to get at this point is the claim that some things are there independent of whether we, as human observers, are there, even though they might have very little to do with our ordinary understanding of matter.

This understanding of the reality of matter does not change much if we start from an alternative definition of reality – not what is there anyway, but what provides the foundation for everything else?

Science tends to proceed on a reductive course, reducing, for example, statements about the medium-sized goods that surround us – bricks, brains, bees, bills and bacteria – to statements about fundamental material objects, such as molecules. These things can then be explained in terms of their constituents, namely their atoms – and so on down to the elementary particles of our current standard model and perhaps even further.

Yet this is no reason to stop our reductionist explanation here, since we can always understand the most basic physical objects in terms of where they are in space and time. Instead of talking about a certain particle that exists at such-and-such a place for such-and-such a period of time, we can simply reduce this to talk about a certain region in space that is occupied between two different times.

We can go even more fundamental. If we take an arbitrary fixed point in space, and a stable unit of spatial distance, we can specify any other point in space by three coordinates. These simply tell us to go so many units up or down, so many units left or right, and so many units back or forth. We can do the same with points in time. We now have a way of expressing points in space-time as sets of four numbers, x, y, z and t, where x, y, and z represent the three spatial dimensions and t the time dimension. In this way, reality can be boiled down to numbers.

Mathematicians reduce numbers to something even more basic: sets, entities that reproduce all the properties of numbers.

←
Turn back to chapter 2 for more on the mathematical conception of reality

But what are these sets? There are two views of mathematical objects that are important in this context. One we have already encountered: the view of them as "Platonic" objects that are not made of matter, they do not exist in space or time, do not change, cannot be created or destroyed, and could not have failed to exist. According to the Platonic understanding, mathematical objects exist in a "third realm", distinct from the world of matter, on the one hand, and the world of mental entities, such as perceptions, thoughts and feelings, on the other.

Alternatively, we can understand mathematical objects as fundamentally mental in nature. They are of the same kind as the other things that pass through our mind: thoughts and plans, concepts and ideas. They are not wholly subjective; other people can have the same mathematical object in their minds as we have in ours, so when we both talk about the Pythagorean theorem, we are talking about the same thing. Still, they do not exist except in the minds in which they occur.

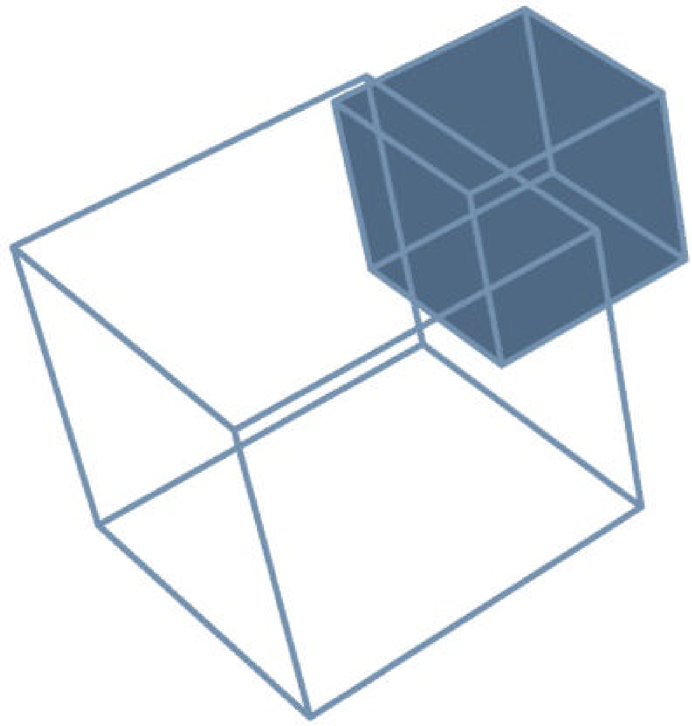
Either of these understandings leads to a curious result. If the bottom level of the world consists of sets, and if sets are not material but are instead some Platonic entities, material objects have completely disappeared from view and cannot be real in the sense of constituting a fundamental basis of all existence. If we follow scientific reductionism all the way down, we end up with stuff that certainly does not look like tiny pebbles or billiard balls, not even like strings vibrating in a multidimensional space, but more like what pure mathematics deals with.

The Platonic view of mathematical objects is hardly uncontroversial, and many people find it hard to get any clear idea of how objects could exist outside space and time. But if we take mathematical objects to be mental in nature, we end up with an even stranger scenario.

The scientific reductionist sets out to reduce the human mind to the activity of the brain, the brain to an assembly of interacting cells, the cells to molecules, the molecules to atoms, the atoms to subatomic particles, the subatomic particles to collections of space-time points, the collections of space-time points to sets of numbers, and the sets of numbers to pure sets. But at the very end of this reduction, we now seem to loop right back to where we came from: to the mental entities.

We encounter a similar curious loop in the most influential way of understanding quantum mechanics: the Copenhagen interpretation. Unlike Wigner's consciousness-based interpretation, this does not assume the wave function collapses when a conscious mind observes the outcome of some experiment. Instead, it happens when the system to be measured (the electron) interacts with the measuring device (the phosphor screen). For this reason, it has to be assumed that the phosphor screen will not itself exhibit the peculiar quantum behaviour shown by the electron.

In the Copenhagen interpretation, then, things and processes describable in terms of familiar classical concepts are the foundation of any physical interpretation. And this is where the circularity comes in. We analyse the everyday world of medium-sized material things in terms of smaller and smaller constituents until we deal with parts that are so small that quantum effects become relevant for describing them. But when it comes to spelling out what is really going on when a wave function collapses into an electron hitting a phosphor screen, we don't ground our explanation in some yet more minute micro-level



structures; we ground it in terms of readings made by non-quantum material things.

What this means is that instead of going further down, we instead jump right back up to the level of concrete phenomena of sensory perception, namely measuring devices such as phosphor screens and cameras. Once more, we are in a situation where we cannot say that the world of quantum objects is fundamental. Nor can we say that the world of measuring devices is fundamental since these devices are themselves nothing but large conglomerations of quantum objects.

We therefore have a circle of things depending on each other, even though, unlike in the previous case, mental objects are no longer part of this circle. As a result, neither the phosphor screen nor the minute electron can be regarded as real in any fundamental sense, since neither constitutes a class of objects that everything depends on. What we thought we should take to be the most fundamental turns out to involve essentially what we regarded as the least fundamental.

In our search for foundations, we have gone round in a circle, from the mind, via various components of matter, back to the mind – or, in the case of the Copenhagen interpretation, from the macroscopic to the microscopic, and then back to the macroscopic. The moral seems to be that either what is fundamental is not material, or that nothing at all is fundamental. ■

→
Turn to chapter 5 for more on evolution and our perception of reality

WHAT IS QUANTUM REALITY MADE OF?

It has been described as the central mystery of quantum theory: the way objects such as electrons and photons of light can act as particles, taking up a discrete position, and as waves smeared out in space and time. Mathematically, this wave-particle duality is embodied by a "wave function", which describes the probabilities that you might find a quantum object in a certain position or travelling at a certain speed. Repeatedly measure an object's position, speed or any other property and the results will match the wave function's probabilities.

It's the sort of maths you might use to tell you the likely state of a rolled die that you can't see. At first, this sort of description was seen as a mathematical convenience – but the reality, it seems, is far more mysterious.

THE emergence of the wave function as a central element of quantum theory was by no means an overnight thing. Mind you, neither was the emergence of quantum theory itself.

The theory was born in 1900 when German physicist Max Planck found that he could explain the baffling spectrum of light emerging from a hot furnace only if the vibrational energy of the atoms giving out the light came in discrete chunks, or quanta. Planck himself thought this was merely a convenient mathematical device. It was left to one Albert Einstein to recognise that quanta were real five years later. He explained the so-called photoelectric effect by showing that the light streaming out of the atoms making up matter consists of untold trillions of these tiny energy packets, now better known as photons.

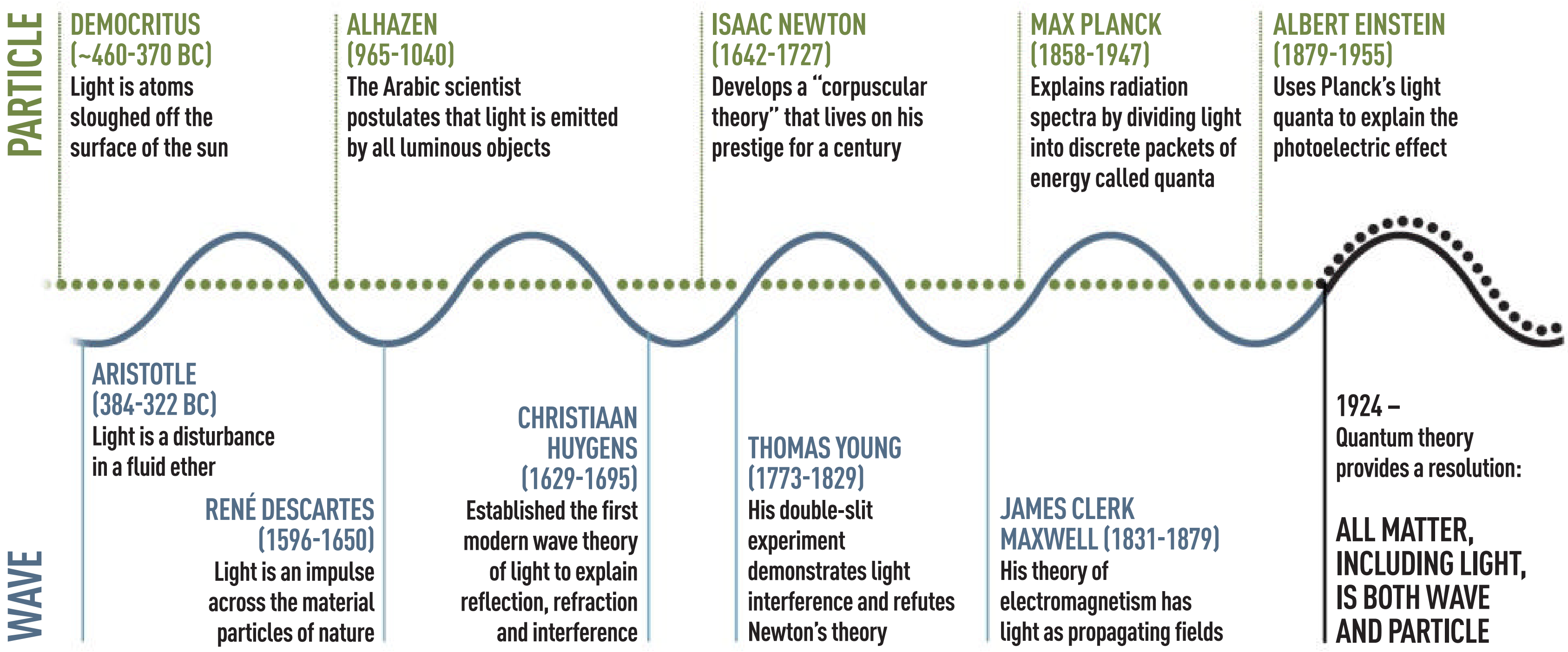
Einstein's idea flew in the face of hundreds of experiments showing that light was like a ripple spreading on a lake or pond. It was just the latest round in a debate about the nature of light that goes back to the philosophers of ancient Greece, and has featured luminaries such as Newton, Descartes and Einstein on one side or the other (see diagram, right). Quantum theory essentially seemed to be saying, in an Alice-in-Wonderland sort of way, that everyone had won, and all must have prizes: light was both a wave and particle.

In 1923, French physicist Louis de Broglie took this idea and ran with it. He proposed not just that light waves could behave like particles, but also that the fundamental particles of matter, things like electrons and protons, could behave like waves. He imagined an electron as a "matter wave" rippling through space. But as the idea was fleshed out mathematically, that interpretation was quietly dropped. The waves associated with quantum particles were waves alright, but they appeared to be totally abstract things, unlike any waves anyone had ever imagined.

It was Erwin Schrödinger – he of cat fame – who realised that actually every quantum system has a wave function associated with it. Schrödinger's wave function is central because it encodes all the possible behaviours for a quantum system. Picture the simple case of an atom flying through space. It is a quantum particle, so you cannot say for sure where it will go. If you know its wave function, however, you can use that to work out the probability of finding the atom at any location you please.

That is good enough for most physicists, who believe the wave function to be merely a probability distribution – a statistical summary of what large

Philosophers and physicists have flip-flopped on whether light is a wave or a particle all the way back to ancient Greece



numbers of measurements would tell you about the whereabouts of the particle. But in the past few years, experiments have seemed to hint it might not be the full story. Perhaps, rather as de Broglie surmised, wave functions are in some way physically real.

An example helps to highlight this subtle difference. Say you arrive at a lake into which a large number of plastic bottles have been thrown. You notice that there are places where the bottles bunch up and places where there are very few bottles. By counting the number of bottles at different locations, you could create a probability distribution, which allows you to estimate the chance of finding a bottle at each point.

But suppose you notice that the bottles are most common where the amplitude of the real waves in the lake peak. Now you realise that the probability distribution isn't the last word – there is a mechanism behind it. Real, physical waves have driven the bottles to their particular locations.

Back in quantum theory, we can similarly ask if the quantum wave function is a probability distribution or the manifestation of a real, underlying wave. The key to answering that question is to come up with a thought experiment in which the two possibilities produce different outcomes. Theorists struggled for years to formulate the question in a tractable way.

In 2012, Matthew Pusey and Terry Rudolph at Imperial College London, with Jonathan Barrett at Royal Holloway University of London, seemed to have struck gold. They imagined a hypothetical theory that completely describes a single quantum system such as an atom but, crucially, without an underlying wave telling the particle what to do, and found that this wave-less theory predicts an outcome different from standard quantum theory. Since the predictions of quantum theory have never been contradicted by experiment, this strongly suggests wave functions come with real waves attached. Using slightly different assumptions, Lucien Hardy at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada obtained a similar result, also in 2012.

It's not a cut-and-dried conclusion, as it rests on certain perhaps reasonable, but not fully tested assumptions about the underlying nature of reality. One is the notion that a quantum system has true properties even before any measurement has been made on it. Another is that the atoms in the thought experiments used to test the new theory are truly independent of one another, so that a measurement made on one does not affect the other. The experiments also take for granted that the laws of cause and effect hold, so that a measurement made on an atom at, say, 3 pm does not affect its state earlier at 1 pm.

If the wave function is real, it is a very weird kind of real. According to the mathematics, Schrödinger's wave function encodes everything there is to know about a single particle in three dimensions. But things get more complicated very quickly. The wave function for two particles exists in an abstract six-dimensional space and for three particles, it exists in nine dimensions, and so on. "We need to expand our imaginations, widen our view of what constitutes fundamental reality," says Antony Valentini of Clemson University in South Carolina. ▮

WAVE, PARTICLE... OR NEITHER?

Experiments demonstrating matter's fundamental wave-particle duality take us deep into a new world of quantum strangeness. Chief among them is an experiment first performed in 1803, ironically to support the wave theory of light: Thomas Young's double-slit experiment. In various iterations over the years, it has showed just how much we don't understand about the underlying nature of reality.

THOMAS YOUNG'S original experiment was simple. He shone light on a screen with two tiny, parallel slits in it, and on another screen a distance behind the first saw alternating vertical fringes of light and dark. It seemed incontrovertible proof that the light was diffracting at the slits and interfering like a water wave.

The real strangeness started with experiments in the 20th century that lowered the light intensity in the double-slit experiment to the point at which only a single photon entered the apparatus at any one time. Place a light-sensitive detector at one or other of the slits and you heard the beep, beep of single particles hitting it. But remove the particle detector and place a light-collecting screen – a kind of long-exposure camera – a distance behind the slits, and the same pattern of light and shade that Young had observed slowly built up.

For Niels Bohr, the great Danish pioneer of quantum physics, the central mystery of wave-particle duality – which applies to any quantum object you care to put through the slits – was nothing less than a principle of the new theory. He called it the complementarity principle. Quantum objects have complementary properties of being a wave and being a particle that can be observed singly, but never together.

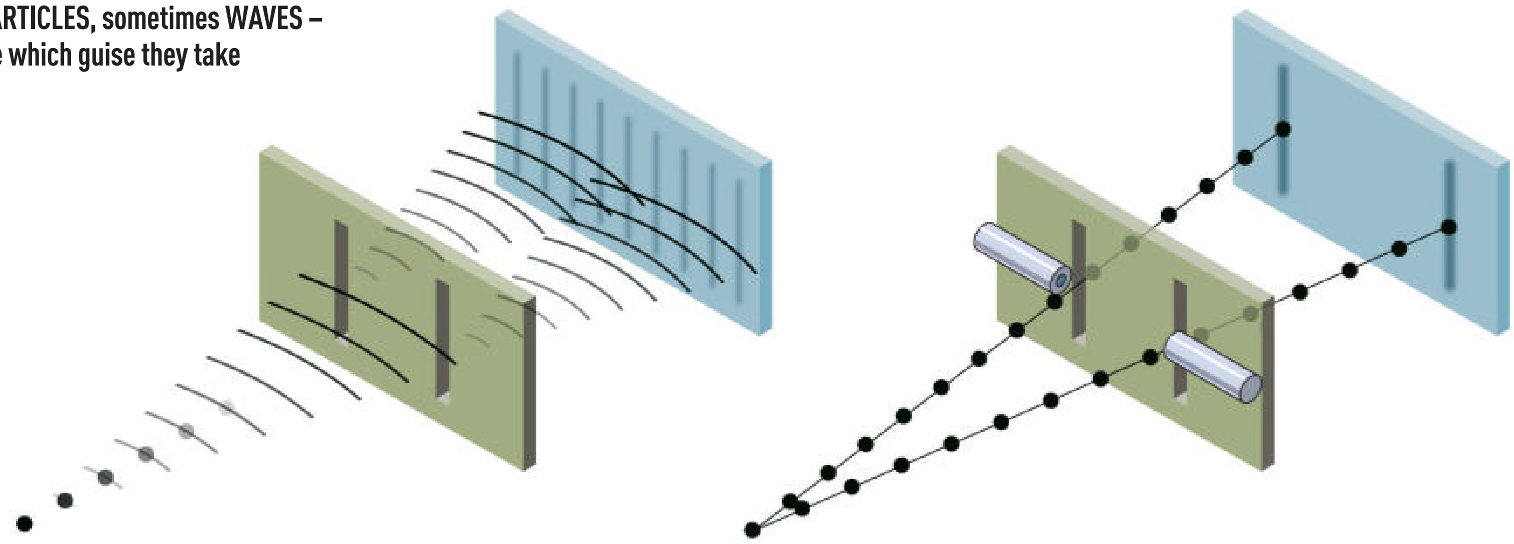
And what determines which guise an object adopts? Bohr laid out a first outline of an answer at a grand gathering of physicists at the Istituto Carducci on the shores of Lake Como in Italy in September 1927: we do. Look for a particle and you'll see a particle. Look for a wave and that's what you'll see (see diagram, above right).

The idea that physical reality depends on an observer's whim bothered the likes of Einstein no end. "No reasonable definition of reality could be expected to permit this," he huffed in a famous paper he co-authored in 1935 with Boris Podolsky and Nathan Rosen. Einstein favoured an alternative idea of an underlying but as-yet inaccessible layer of reality containing hidden influences that "told" the photon about the nature of the experiment to be performed on it, changing its behaviour accordingly.

There is more to this than wild conspiracy theory. Imagine an explosion that sends two pieces of shrapnel in opposite directions. The explosion obeys the law of conservation of momentum, and so the mass and velocity of the pieces are correlated. But if you know nothing of momentum conservation, you could easily think that measuring the properties of one fragment determines the properties of the other, rather than both being set at the point of explosion. A similar hidden reality might be responsible for goings on in the quantum world.

In 1978, the physicist John Wheeler hit upon a way to settle the issue of what told the photon how to behave, using an updated version of the double-slit

The classic double slit experiment seems to suggest quantum objects such as electrons are sometimes PARTICLES, sometimes WAVES – and we decide which guise they take



A stream of single electrons is fired at two slits and measured on a screen behind. An interference pattern forms, as if each electron were a WAVE that passed through both slits at once

Measure the electrons first at the slits, however, and you see individual PARTICLES passing through one slit or the other – and the interference pattern on the screen disappears

experiment. Photons would be given a choice of two paths to travel in a device known as an interferometer. At the far end of the interferometer, the two paths would either be recombined or not. If the photons were measured without this recombination – an “open” interferometer – that was the equivalent of putting a detector at one or other of the slits. You would expect to see single particles travelling down one path or the other, all things being equal, splitting 50:50 between the two (see diagram, overleaf).

Alternatively, the photons could be measured after recombination – a “closed” setting. In this case, what you expect to see depends on the lengths of the two paths through the interferometer. If both are exactly the same length, the peaks of the waves arrive at the same time at one of the detectors and interfere constructively there: 100 per cent of the hits appear on that detector and none on the other. By altering one path length, however, you can bring the wave fronts out of sync and vary the interference at the first detector from completely constructive to totally destructive, so that it receives no hits. This is equivalent to scanning across from a bright fringe to a dark one on the interference screen of the double slit experiment.

Wheeler’s twist to the experiment was to delay choosing how to measure the photon – whether in an open or a closed setting – until after it had entered the interferometer. That way, the photon couldn’t possibly “know” whether to take one or both paths, and so if it was supposed to act as a particle or a wave.

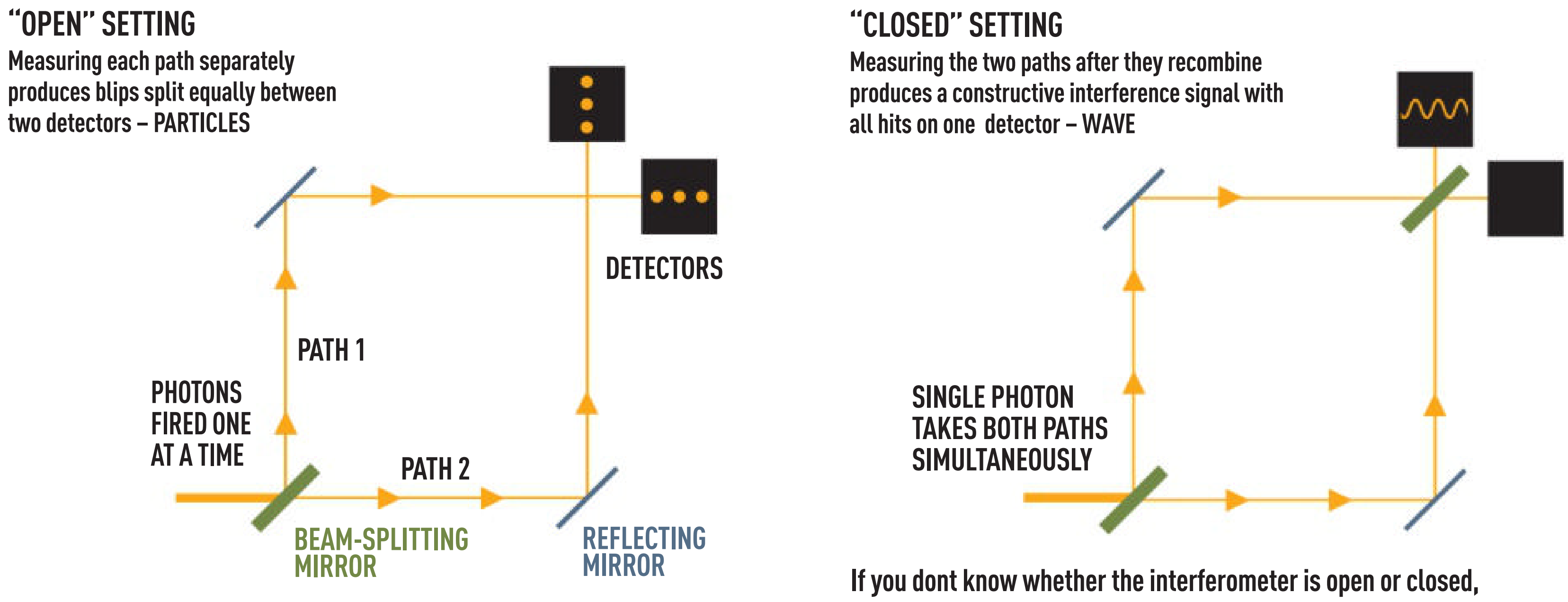
It was almost three decades before the experiment could actually be done. In 2007, Alain Aspect and his team at the Institute of Optics in Palaiseau, France, managed it. Whenever they chose at the last instant to measure the photons with a closed interferometer, they saw wave interference. Whenever they chose an open interferometer, they saw particles.

There was no getting round it. Wave and particle behaviours really do seem to be two sides of one coin representing material reality. As to which way it flips – well, you decide.

In 2012, however, came a new twist on the double-slit experiment, in which the decision of how to measure the photon, as a particle or as a wave, was itself a quantum-mechanical one – not a definite yes or no, but an indeterminate, fuzzy yes-and-no. Researchers did this by using light to control the detector designed to probe the light. First they prepared a “control” photon in a quantum superposition of two states. One of these states switches the interferometer to an open, particle-measuring state, and the other to a closed, wave-measuring state. Crucially, they only measured the state of the control photon after they had measured the experimental “system” photon passing through the interferometer.

This meant that as far as they were concerned, the system photon was passing through an interferometer that is both open and closed; ›

According to how it is set up, an interferometer can be used to "prove" light is particles, waves – or nothing of the sort



If you dont know whether the interferometer is open or closed, something is measured – but it looks like neither PARTICLE nor WAVE

they didn't know whether they were setting out to measure wave or particles.

And what they saw depended on the control photon. Measurements of the system photons made without ever checking the corresponding measurements of the control photons produced a distribution of hits on the two detectors that was the signature neither of particles or waves, but some mixture of the two. If particle is black and wave is white, this is some shade of grey.

Doing the same, but this time looking at the control photon measurements as well, was like putting on a pair of magic specs, with grey separating clearly into black and white. System photons that had passed through an open interferometer were clearly particles. Those that passed through a closed interferometer looked like waves. The photons revealed their colours in accordance with the kind of measurement the control photon was being made.

It gets yet stranger. Quantum mechanics allows you to put the control photon not just in an equal mix of two states, but in varying proportions. That is equivalent to an interferometer setting that is, say, open 70 per cent of the time and closed 30 per cent of the time. If you measure a bunch of system photons in this configuration, and look at the data before putting on our magic specs, you see an ambiguous signature once again – but this time, its shade of grey has shifted closer to particle black than wave white. Put on the specs, though, and you see system photons 70 per cent of which have seemingly – but clearly – behaved as particles. The remaining 30 per cent acted as waves.

These results leave us grappling for words. "Complementarity shows only the two ends, black and white, of a spectrum between particle and wave," says Radu Ionicioiu of the Institute for Quantum Computing in Waterloo, Canada, who performed some of the 2012 tests. "This experiment allows us to see the shades of grey in between."

It provides support for the sort of interpretation of wave-particle duality favoured by Bohr, and at the heart of his favoured "Copenhagen interpretation" of quantum theory. "Particle" and "wave" are concepts we latch on to because they seem to correspond to guises of matter in our familiar, classical world. But attempts to describe true quantum reality with these or any other black-or-white concepts are doomed to failure.

These latest versions of Young's double slit experiment take us straight back into Plato's cave, says Ionicioiu. In the ancient Greek philosopher's allegory, prisoners shackled in a cave see only shadows of objects cast onto a cave wall, never the object itself. A cylinder, for example, might be seen as a rectangle or a circle, or something in between. A similar thing is happening with the basic building blocks of reality. "Sometimes the photon looks like a wave, sometimes like a particle, or like anything in between," says Ionicioiu. In reality, though, it is none of these things; and what it is, we do not have the words or the concepts to express. ▮

WHO KILLED SCHRÖDINGER'S CAT?

Quantum theory's suggestion that underlying reality is basically fuzzy, only crystallising into certainty on observation, is a world away from our everyday experience of a world in which things have a defined guise and move in a certain way.

It's a weirdness exemplified by Schrödinger's cat – a thought experiment invented by Austrian physicist Erwin Schrödinger in 1935 to demonstrate just how absurd quantum theory's conclusions about reality seemed to be.

SCHRÖDINGER'S thought experiment places a real cat in a box with a vial of poison that can be smashed, releasing gas that kills the cat, by a mechanism that depends on whether a radioactive atom decays or not. Radioactive decay is a quantum process, and according to the underlying mathematics of quantum theory, the radioactive atom exists in a quantum superposition state of decayed and not decayed before it is measured to ascertain which.

When you open the box to find out what's happened, you'll find a cat that's dead or alive. But what state is it in before you open it, when the radioactive decay might have happened, or might not: dead and alive?

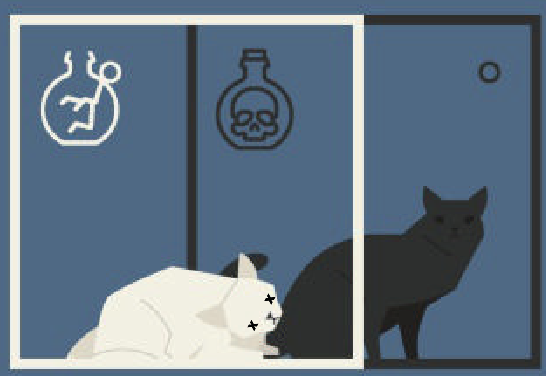
The answer is there is no answer – only various interpretations of what the quantum mathematics might be telling us. Some of the most prominent are described and depicted overleaf. ›

The Schrödinger's cat experiment illustrates the supposed absurdity of quantum theory, with objects existing in uncertain states before they are observed. Within a box, a random radioactive particle decay may break a vial of poison gas that kills a cat. If the cat is dead when you open the box, what has happened?

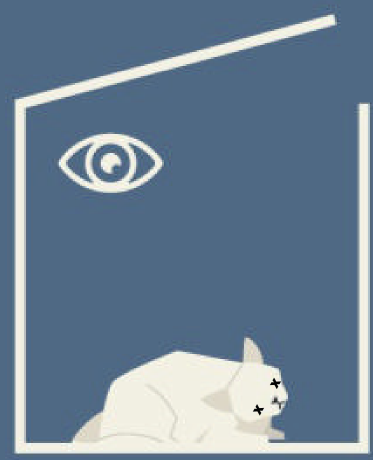
Before observation

After observation

STANDARD (COPENHAGEN) INTERPRETATION

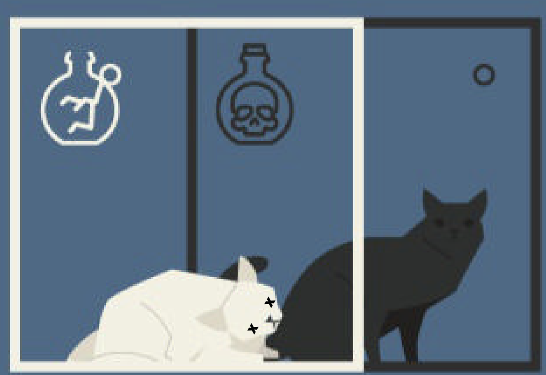


The cat is simultaneously alive and dead

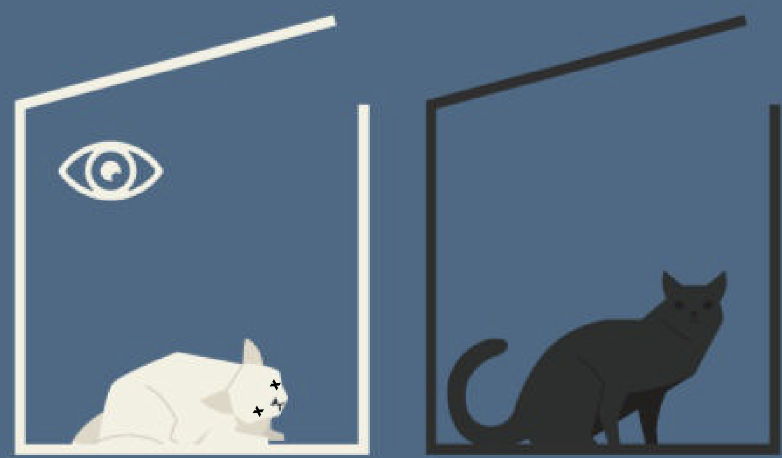


The cat is dead.
Your measurement killed the cat

MANY WORLDS INTERPRETATION



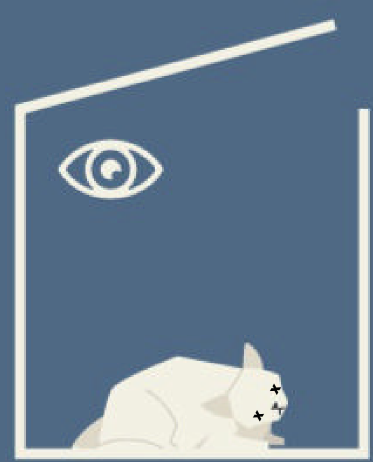
The cat is simultaneously alive and dead



The universe splits.
Your cat is dead, but in a parallel world it remains alive

OBJECTIVE COLLAPSE THEORY

The cat is either alive or dead



The cat is dead.
It may have been dead for some time

THE COPENHAGEN INTERPRETATION

See diagram, left

Critics of this view claim it is no explanation at all. But the Copenhagen interpretation, devised by quantum pioneer Niels Bohr and others in the Danish capital in the 1920s, remains by far the dominant way to explain away quantum weirdness. Often described as the "shut up and calculate" option, it basically says that since we are conditioned to think in terms of the classical world around us, the quantum world is in essence unknowable. Quantum theory is an extremely effective tool for making predictions, but no more than that. When we observe the quantum world, we force it to conform to our preconceptions – "collapsing" it into a classical shadow of itself. So don't ask who killed Schrödinger's cat – you did.

MANY WORLDS

See diagram, left

For a disciple of many worlds, the quantum realm is intrinsically fuzzy. Observing it does not create a single defined reality, but splits reality into as many parallel worlds as there were options for what might have been observed. When we open the box to see what's happened to Schrödinger's cat, we follow the path into one parallel world where whatever outcome we measure has happened, while a parallel us measures the opposite outcome in a different world. The quantum universe is constantly sprouting new worlds as it reaches similar branching points

The theory was the brainchild of Princeton graduate student Hugh Everett III in the 1950s, and initially few were convinced. Everett described a journey to Copenhagen in 1959 to explain his idea to Niels Bohr as "hell... doomed from the beginning". In recent decades, however, many worlds has enjoyed something of a revival as ideas of a "multiverse" of parallel universes have permeated cosmology. That was not before Everett, who believed his theory guaranteed him immortality in some world or other, had eaten, drunk and chain-smoked himself to an early death in 1982. You can read more about the implications of many worlds for ourselves on page 86.

OBJECTIVE COLLAPSE

See diagram, left

In this picture, there's no need for an observer to destroy an object's quantum nature – it happens spontaneously all the time, like radioactive particles randomly decaying. The more particles there are, the more speedily this happens. We are clodhopping bundles of non-quantum stuff that infect any quantum objects we measure with classical physics.

THE DE BROGLIE-BOHM INTERPRETATION

This idea is based on classic work by quantum pioneers Louis de Broglie and David Bohm. It says that the bewildering nature of quantum theory implies that there must be additional stuff we're not seeing. In this case it's "pilot waves" that guide the evolution of quantum states on some hitherto unexplored layer of reality.

Einstein was an early fan, although he later cooled, and some experiments had seemed to rule out such hidden features. But the de Broglie-Bohm interpretation has staged a comeback, buoyed by advances in quantum information theory and recent experiments suggesting that quantum wave functions might be in some way real.

QUANTUM BAYESIANISM

Taking its cue from Bayesian probability, in which a 50 per cent probability of rain in the weather forecast is immediately updated to a 100 per cent probability when you open the curtain and see it's actually raining, quantum Bayesianism asserts that quantum uncertainty is all in our minds. Our confusion about how reality works at the finest scales is merely a product of our imperfect information about it. So open up the box, and just find out what really happened – simple. The only problem is that if quantum theory is all just about our state of mind, this leaves us with no theory of how reality actually works at all.

RELATIONAL QUANTUM MECHANICS

In Einstein's relativity there is no absolute answer to whether two events are simultaneous – it depends on your point of view. Similarly, this interpretation asserts that no single observer can ever be in possession of all the facts about a quantum state – we are part of any measurement we make, so lack any full view of it. The brainchild of Italian physicist Carlo Rovelli, it's another variant on the idea that quantum weirdness is all an illusion born of imperfect information.

All of the above interpretations struggle, however, with the latest iteration of Schrödinger's original thought experiment. This has two observers checking on two cats in two labs that are themselves in a quantum superposition – and seems to indicate that on 1 out of 12 occasions, the two observers will make observations about each other's cats that are directly contradictory. This "Frauchiger-Renner" paradox, first posed in 2016, has generated lively controversy, with no one quite yet clear whether it represents a serious challenge to quantum theory, to our conceptions of reality, to both – or to neither, because there is some flaw in the way the thought experiment is set up. ▮

REALITY, CAUSALITY AND FREE WILL

It is clear there is a deep mismatch between how we think reality should work, and what quantum theory seems to tell us about how it works. With thought experiments and experiments in the lab, researchers have begun to prise apart what exactly those differences consist of. The results suggest that to achieve some deeper explanation, we may have to give up cherished principles of reality.

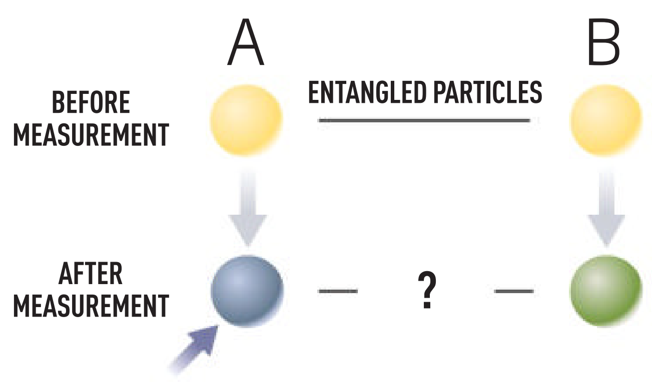
MANY experiments expose the sheer apparent strangeness of quantum reality. But quantum weirdness perhaps reaches its apogee at the half-silvered mirror: a mirror that reflects half the light that hits it, but lets the other half pass through. Let light hit the mirror in the right way, and it is not just the light beam that is split, but individual photons. They become in effect two photons. One of them passes through the mirror, and the other is reflected.

Each of these photons has particular properties, for example of spin, a quantum-mechanical quantity that can be envisaged rather like a rotation in space. But something very odd happens when you decide to measure these spins one after the other. You can do this over and over again, each time measuring the two spins relative to different things – the lab floor, the direction of the prevailing wind outside, the direction in which a fly is walking across the ceiling above. After a while, a chill runs down your spine. A pattern emerges: each time, the outcome of the second measurement depends on how you chose to make the first measurement.

This is something we cannot explain with normal, classical conceptions of reality. It is entanglement: the ability of quantum objects that were once related to apparently influence each other's properties when subsequently separated, even by a long way. Einstein called it "spooky action at a distance", and it nourished his belief that the workings of an undiscovered, hidden layer of reality explained the quantum world.

It is tempting to seek succour in such "normal" physical explanations, and so maintain our standard perceptions of reality. Some undetected influence must fly between the two photons; something physical must pass from one to inform the other of the information that has been extracted. Whatever form that influence might take – a photon, some other exchanged particle or perhaps a type of wave? – a good guess is that it will not travel faster than the speed of light. As embodied in Einstein's own theories of relativity, that is a fundamental speed limit to any kind of usable information flying through the universe. This prevents all sorts of unpleasant consequences, such as violations of causality, allowing information to travel backwards

The strange correlations between quantum objects, however far apart they are, can only be explained by abandoning some fundamental assumption



Measure the state of A, and the state of B instantaneously changes

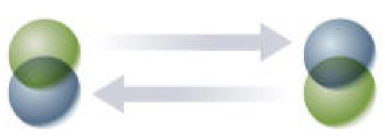
Abandon REALITY

The correlations are explained by a physical influence travelling through a hidden level of reality

Abandon RELATIVITY

Some unseen influence in our level of reality travels faster than the speed of light

Abandon CAUSALITY



This is no definite cause and effect in the quantum world: B is affecting A as much as A is affecting B

Abandon FREE WILL

Some external force is manipulating the experimenters so they always see correlations

in time. Allow violations of relativistic causality, and we could all be lottery millionaires.

Hidden physical influences of the less outlandish sort, which obey relativity, can be tested for relatively easily. First you separate two entangled photons by a huge distance. The second photon is sent away – to the International Space Station, say – with instructions to carry out a measurement at a precise time. An instant before that measurement occurs, you measure the first photon. Time it right, and there is not enough time for any influence to travel between the two, even at the speed of light.

We haven't done the space station test, but we have done similar things many times on Earth. Each time, when the report of the second measurement comes back, the weird influence has still been felt. The second photon responds as if it were aware of what happened to the first. Experiments by Nicolas Gisin and his colleagues at the University of Geneva in Switzerland in 2008 showed that any spooky influences travelling 18 kilometres through a fibre-optic network must be travelling at a minimum of 10,000 times the speed of light. The experiments have also been done over hundreds of kilometres in free air, and even using light from distant galaxies, with similar results.

For Gisin, this means that the dimensions of reality we move in cannot possibly contain a physical explanation for a more fundamental quantum reality of the stamp of Einstein's hidden layers. "There is no story in space and time that tells us how the correlations happen," he says.

Unless there is something fundamental that we have wrong. We humans are suckers for causal order, looking back in time to trace the cause of any event. Even more basically, we are determined determinists, blithely assuming that every event actually has a cause. That seems to work reasonably well in our large-scale everyday world, but when it comes to the nitty-gritty of the underlying quantum reality, can we be so sure?

Theorist Caslav Brukner and his colleagues at the University of Vienna in Austria have composed thought experiments suggesting that might not be the case: different causal orders can exist simultaneously in the quantum world. Just as quantum particles can be in two places at once, so seemingly can they be in two moments at once.

We live in space-time, and experience causal order › within it, yet causal order is not apparently fundamental to quantum theory. If we accept quantum theory as the most fundamental description of reality that we have, it means that space-time itself is not fundamental, but emerges from a deeper, currently inscrutable quantum reality.

←
See page 41 for more on the nature of space-time

If we accept quantum theory, that is. All the havoc quantum theory wreaks with cherished notions of reality, relativity and causality raises a natural question: is quantum theory itself the problem? For all its successes, perhaps all its randomness, uncertainty and spooky influence is just because quantum mechanics is incomplete. It might simply not supply all the information we need to explain why things are as they are.

But that doesn't seem to wash, either. Quantum theorists investigating what would happen if a theory were to provide an additional, arbitrary amount of information about the correlations between two entangled particles have shown that the outcomes of the measurements would remain just as random and unpredictable as they do with quantum theory, where you can only ever predict with a certain probability what measurement outcome you will see. Follow that, and it seems that deep down, the universe is spontaneous. To flip Einstein's famous quote, God does play dice. Things are intrinsically random.

Unless you ask an even more fundamental question about reality and our relation to it. In quantum experiments, your choice influences the outcome of a measurement. But what if it is not actually your choice? What if something else were forcing your hand, making you perform the experiments such that the correlations always appear?

This takes us into the domain of human free will, a slippery territory where philosophers are usually more abundant than physicists. It sounds vaguely loopy, yet some serious physicists think that a lack of free will – that we are participants in something of a cosmic puppet show – might be the best way to save us from all the weirdness and loss of relativity and causality implied by quantum correlations.

Nobel laureate Gerard 't Hooft of the University of Utrecht in the Netherlands, for example, is one who finds the idea of quantum correlations that defy notions of space and time "difficult to buy". He thinks the answer might instead lie in an extreme form of "superdeterminism" in which human minds are set on a trajectory of choices, such as what to make a quantum measurement relative to, from which they are powerless to deviate.

→
Turn to page 88 for more on the problems of human agency and free will

Others are less impressed. "Invoking conspiratorial correlations among all the brains, measuring instruments, and subatomic particles in the universe to make it 'look like' quantum mechanics is true is vastly stranger than the thing it's supposedly trying to explain," says Scott Aaronson, a quantum physicist at the University of Texas at Austin. In essence, he says, there is little difference between invoking something like that and invoking a superhuman deity.

It could be that the growing disconnection between our experience of the world and the results of quantum experiments are simply a modern version of the ever-more complex epicycles that Ptolemy and those who followed him used to explain the motions of the heavenly bodies. The problem back then was that we could only see the planets as revolving around Earth; it took Copernicus to turn things around, and suddenly all was plain and simple.

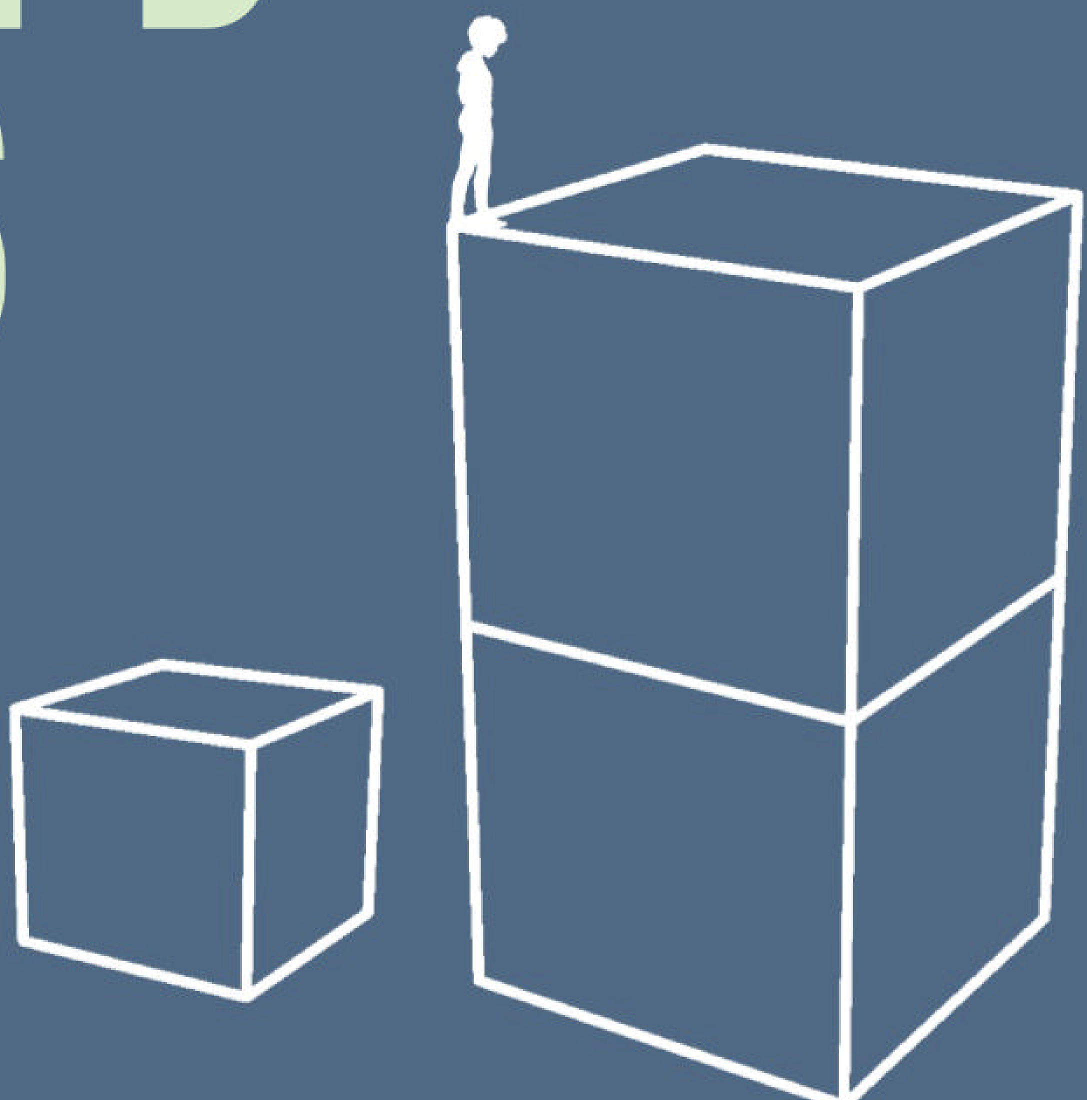
Perhaps we have constructed theories such as relativity and quantum theory with a similarly limited view, in thrall this time to a sense of space and time that might not exist beyond ourselves. Time and space might be important to us because we evolved to perceive them; but are they as important to the world?

↓
Read on to the next chapter for more on evolution and our perception of reality

When the light shines on that half-silvered mirror, what we see is hardly a reflection of the world as we would like to know it. Reality, relativity, causality, free will, space and time: it seems they can't all be right. But we can't quite tell which ones are wrong. ▮

CHAPTER 5

REALITY AND US



There is one great barrier between us and any understanding of objective reality – ourselves. Our view of reality is highly subjective: our senses filter incoming information and our brains process it, to the extent that we can't be sure what relation our internal representations bear to external reality.

The search for the physical and material basis of reality, as covered in the previous chapters, represents an attempt to take these subjective perceptions out of the equation, and find in scientific laws some common, objective grounds for reality's workings that we can all agree on. But we ourselves may still represent a limit to that enterprise. Mathematically based laws fail to explain the very thing that creates them and the desire to understand reality – our minds.

It might even be that we are hardwired not to see the objective truth of the world around us. Charles Darwin's theory of evolution by natural selection has over the past century and a half given us a peerless picture of our own origins and how the natural world around us works. But it comes with a mighty sting in its tail when it comes to our perception of the world, as cognitive scientist Donald Hoffman reveals.

LIFE insurance is a bet on objective reality – a bet that something exists, even if I cease to. This bet seems quite safe to most of us. Life insurance is, accordingly, a lucrative business.

While we are alive and paying premiums, our conscious experiences constitute a different kind of reality, a subjective reality. My experience of a pounding migraine is certainly real to me, but it wouldn't exist if I didn't. My visual experience of a red cherry fades to an experience of grey when I shut my eyes. Objective reality, I presume, doesn't likewise fade to grey.

What is the relationship between the world out there and my internal experience of it – between objective and subjective reality? If I'm sober, and don't suspect a prank, I'm inclined to believe that when I see a cherry, there is a real cherry whose shape and colour match my experience, and which continues to exist when I look away.

This assumption is central to how we think about ourselves and the world. But is it valid? The idea that what we perceive might differ from objective reality dates back millennia. The philosopher Plato proposed that we are like prisoners shackled in a fire-lit cave. The action of reality is happening out of sight behind us, and we see only a flickering shadow of it projected onto the cave wall.

ANXO VIZCAÍNO

Modern science largely abandoned such speculation. For centuries, we have made stunning progress by assuming that physical objects, and the space and time in which they move, are objectively real. This assumption underlies scientific theories from Newtonian mechanics to Albert Einstein's relativity to Charles Darwin's theory of evolution by natural selection.

Natural selection, you might think, gives a simple reason why our senses must get it largely right about objective reality. Those of our predecessors who saw more accurately were more successful at performing essential tasks necessary for survival, such as feeding, fighting, fleeing and mating. They were more likely to pass on their genes, which coded for more accurate perceptions. Evolution will naturally select for senses that give us a truer view of the world. As the evolutionary theorist Robert Trivers puts it: "Our sense organs have evolved to give us a marvellously detailed and accurate view of the outside world."

The truth of such statements can be tested with mathematical rigour using the tools of evolutionary game theory, introduced in the 1970s by John Maynard Smith. In this theory, different strategies for coping with the natural world can be set against each other in simulations to see which approaches are fitter – in the sense of producing more offspring.

In the case of perception, we can study how "truth" strategies, which see objective reality as it is, fare against "pay-off" strategies, which see only survival value. Take oxygen. Too much or too little oxygen in the air kills us; a narrow range keeps us alive. Now imagine living in an environment where the level of oxygen varies considerably, and you have to make ›

PROFILE
DONALD HOFFMAN

Donald Hoffman is a cognitive scientist at the University of California, Irvine, and author of *The Case Against Reality: Why evolution hid the truth from our eyes*

survival judgements about whether to venture outside.

For the sake of this example, the amount of oxygen in the air is taken to be an objective truth. You might imagine seeing it on a colour scale from red for low to green for high. That's the truth strategy: you know the truth, but you don't know if you'll die. A pay-off strategy would mean seeing red colours for levels of oxygen that kill you, and green for those that don't. You see what you need to survive, but don't see the objective truth of how much oxygen there is.

The objective truth I started seeing a decade ago, in simulations conducted together with my graduate students Justin Mark and Brian Marion at the University of California, Irvine, is that evolution ruthlessly selects against truth strategies and for pay-off strategies. An organism that sees objective reality is always less fit than an organism of equal complexity that sees fitness pay-offs. Seeing objective reality will make you extinct.

If this seems hard to swallow, suppose you are writing a novel on a laptop, and the novel's icon on the desktop is green, rectangular and in the centre of the screen. Does this mean that the novel itself is green, rectangular and in the centre of your laptop?

Of course not. The desktop interface is there to mask a complex reality of software, circuits and digital 1s and 0s to provide a simple way to interact with it. If you actually had to flip computer bits to write a novel, you would switch to pen and paper.

That, evolutionary game theory predicts, is what evolution has done for us. Natural selection has given us sensory systems that are a simplifying user interface for the complexity of the world. Space, as we perceive it around us, is a 3D computer desktop, with tables, chairs, the moon and mountains icons within it.

In other words, our senses constitute a virtual reality. If you play the video game *Grand Theft Auto* with a virtual-reality add-on, you see a 3D world with 3D objects, such as a black steering wheel in front of you.

If you turn your head, however, the steering wheel disappears. Indeed, it ceases to exist, because it only exists when we are looking where it should be in the simulation. The reality that exists – circuits and software again – is utterly unlike a steering wheel. But it prompts you to create a steering wheel when it is needed, and to destroy it when it isn't.

In like manner, we create an apple when we look, and destroy it when we look away. Something exists when we don't look, but it isn't an apple, and is probably nothing like an apple. The human perception of an apple is a data structure that indicates something edible (a fitness pay-off) and how to eat it. We create these data structures with a glance, and erase them with a blink. Physical objects, and indeed the space and time they exist in, are evolution's way of presenting fitness pay-offs in a compact and usable form.

But hang on, drop the apple. A lion on the African savannah isn't just an icon in your interface. It has agency, and can kill you, so it must be objectively real.

I wouldn't mess with a lion, for the same reason I wouldn't carelessly drag the green icon of my novel to the virtual recycle bin. Not because I take that icon literally, and think the novel is green and rectangular. But I do take that icon seriously: if I drag it to the bin, I could lose all my work.

The objection that a lion must be objectively real because anyone who looks over there sees a lion that we can all agree looks like a lion – so it isn't unique to our subjective experience – isn't a valid one, either. Humans agree about what we see because we have all evolved a similar interface. The interfaces of some other species, such as prey mammals, may have icons for lions that are similar to ours, and that guide actions similar to ours, such as keeping far away from them.

That leaves the fact that treating our observed, subjective reality as objective reality has allowed us to create scientific theories – frameworks that allow us to make predictions about how the world works, and so are presumably part of an objective reality that exists outside our heads. But here too there are hints from deep within science itself that perception and reality don't match.

Quantum theory is our best physical theory of fundamental reality. But with its counter-intuitive effects of "spooky action at a distance" and the perennial mystery of the dead-yet-alive Schrödinger's cat, it drives a coach and horses through cherished ideas from our classical realm of experience: that objects have definite values of the properties pertaining to them, that those properties don't depend on how they are observed, and that influences propagate no faster than light.

←
Turn back to page 65 for more on Schrödinger's cat and its lessons about quantum reality

This is jolting if we assume that objects and their measurable properties are part of an objective reality. But it is no surprise if we think of objects and their properties as data structures created as needed to represent fitness pay-offs. In this case, the values of properties will depend on when and how we create them.

This approach aligns with the quantum-Bayesian interpretation of quantum theory, or QBism, in which the uncertainty inherent in quantum observations is all in the minds of the observers. As three pioneers of QBism, Christopher Fuchs, David Mermin and Rüdiger Schack have put it, "A measurement does not, as the term unfortunately suggests, reveal a pre-existing state of affairs. It is an action on the world by an agent that results in the creation of an outcome – a new experience for that agent. 'Intervention' might be a better term."

If our team's evolutionary ideas are true, that might lend momentum to models of quantum theory that see quantum states, and the mathematical and interpretational structures around them, as "epistemic" – reflecting not necessarily reality, but just our state of knowledge of it.

But it goes further. Even perceptions as seemingly fundamental as space and time might not actually be part of objective reality. That insight could inform our search for theories that unite the two great theories at the heart of modern physics.

For decades, we have tried and failed to reconcile quantum theory with general relativity, Einstein's theory of gravity that dictates how the universe works on large scales. At a very basic level, these theories fail to agree on the nature of space and time.

←
For more on unified theories of physics, turn back to page 48

General relativity demands that space-time, the four-dimensional structure that space and time together form, is smooth and continuous, whereas a quantum description requires a pixelated description. As the theoretical physicist Nima Arkani-Hamed has said: "Almost all of us believe that space-time doesn't exist, that space-time is doomed, and has to be replaced by some more primitive building blocks." Admittedly, no one yet knows what those might be – but our insights suggest the hunch they must be replaced is right.

It isn't just in physics where we may need to overhaul our ideas about reality to make progress. Another is › in solving the "hard problem" of consciousness. This problem of how and why our brains generate conscious experience remains intractable despite centuries of thought. As biologist Thomas Huxley put it in 1869: "How it is that anything so remarkable as a state of consciousness comes about as a result of irritating nervous tissue, is just as unaccountable as the appearance of the djinn, when Aladdin rubbed his lamp."

The brain-exciting technology of transcranial magnetic stimulation (TMS) illustrates how little progress we have made. Suppose we place a TMS unit near your scalp, on the right side of your head, near an area of the occipital cortex called V4. We turn on the device, and its strong and focused magnetic fields inhibit neural activity nearby. All colour drains away from the left half of your visual world; you see only shades of grey. We turn off the device, and the colour seeps back in.

Neuroscience has turned up hundreds of such correlations between patterns of neural activity and specific conscious experiences. Most attempts to explain these correlations assume that the neural activity causes, or somehow gives rise to them. But how, precisely? What neural activity causes the taste of vanilla, and why doesn't it cause the taste of chocolate? In a network of interacting neurons, how exactly do changes in voltage, or in the flow of sodium, potassium and calcium ions through pores in neural membranes, create an individual conscious experience?

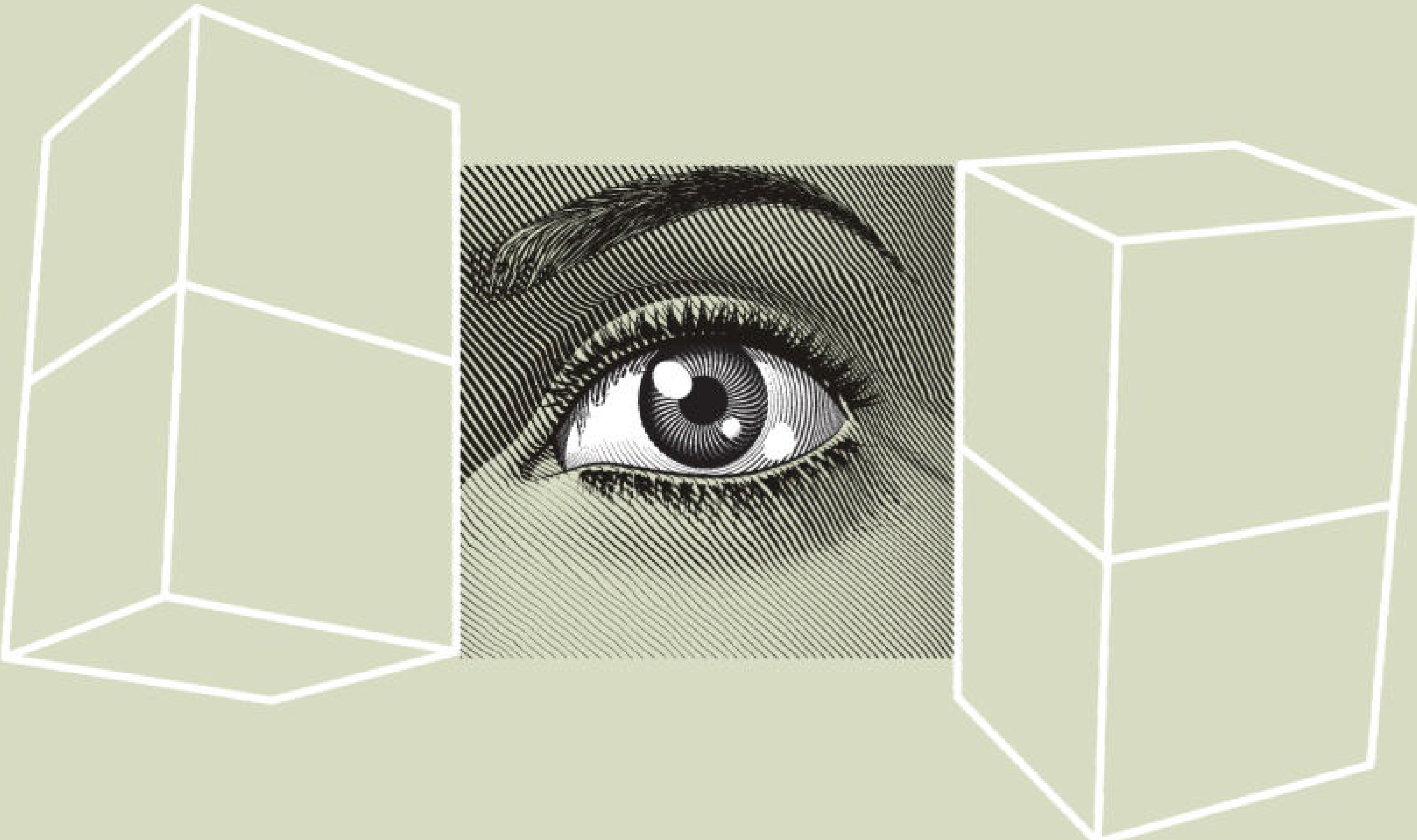
There are no theories, and few plausible ideas. But if we are trying to find the answer to the problem of conscious experience in the firing of neurons in space and time, when those neurons themselves are just icons in a subjective interface, perhaps that is no wonder.

So how can we break through our subjective perception and find objective reality? I don't know. But my collaborators and I are currently trying to solve the hard problem of consciousness by building a theory in which the underlying reality emerges from a vast network of interacting conscious agents and their experiences. Our space-time interface – together with shapes, colours and other sensory properties – is like a visualisation tool that some agents, like us, use to simplify and interact with this network.

This hypothesis, of course, is probably wrong. But the point of science is to be precise, so we can find out what precisely we have wrong. Our theory of interacting conscious agents fails if its predictions don't square with well-tested results of classical physics, quantum theory, general relativity, evolution by natural selection and so on in our space-time interface.

And the argument turns on itself. We used the theory of evolution by natural selection to discover that what we perceive isn't objective reality, but an interface with it. Now we realise that evolution itself may be just an interface projection of deeper dynamics stemming from a network of conscious agents. The goal ahead is to work out those dynamics in detail, and figure out how, precisely, they map onto our space-time interface. This will allow us to make empirical predictions testable by experiments within our subjective reality.

Science so far has focused its search on this immediate reality. What it has found can guide our theories and test our predictions as we try to look beyond it, to find the nature of objective reality. Can we do it? Just like I take out life insurance, I'm betting we can. ▮



WHAT IS CONSCIOUSNESS?

How we subjectively perceive reality, and what relationship our perceptions have with any external, "objective" reality, leads us to one of the great outstanding mysteries of science – the nature of our conscious experience. It is everything we feel, but even modern neuroscience is stumped as to what it consists of.

IT IS not easy having Cotard's syndrome. People with this extremely rare neuropsychological condition are convinced they are dead or do not exist. They will often not see the need to do basic things to stay alive – eat, for example. But the really odd thing is that in even though people with Cotard's syndrome feel they don't exist, there is still an "I" experiencing that feeling. What is that "I"?

The French philosopher René Descartes, of "I think, therefore I am" fame, was convinced that the body and conscious mind are two different substances: the first is made of matter, the latter is immaterial. These "dualist" ideas influenced neuroscience until a few decades ago, but things have moved on. Today, it is widely accepted that our brains give rise to this sense of being a self located in space and continuous in time, constantly interacting with external reality through our sensory experience – of consciousness.

JOLYGON/ISTOCKPHOTO

But how? That is a raging debate. At its heart is what philosopher David Chalmers termed the "hard problem" of consciousness. How can physical networks of neurons produce experiences – love, pain, colour, and so on – that appear to fall outside the material world, and are purely internal to ourselves? As philosopher Thomas Nagel put it in the 1970s: you could know every detail of the physical workings of a bat's brain, but still not know what it is like to be a bat.

Broadly speaking, those trying to solve the hard problem fall into two camps: those who think that consciousness is something real and those who say it's a mirage. The former camp argues that consciousness is a fundamental component of the universe, one that exists alongside matter and has properties which, perhaps conveniently, cannot be explained by our present understanding of physics. Taken to an extreme, says Chalmers, this idea can lead to panpsychism, the view that all matter – even inanimate objects like rocks – is imbued with some degree of consciousness.

Even without tackling that particular Pandora's ›

“The brain is a system continually trying to prove its existence”

box, this camp faces a daunting challenge. Conscious thought can influence the body: a conscious desire to move your arm results in physical movement, and that physical movement in turn influences the world around us. But the fundamentals of how our mental states create this “agency” remain hazy.

→
Turn to page 88 for more on the mysterious human power of agency

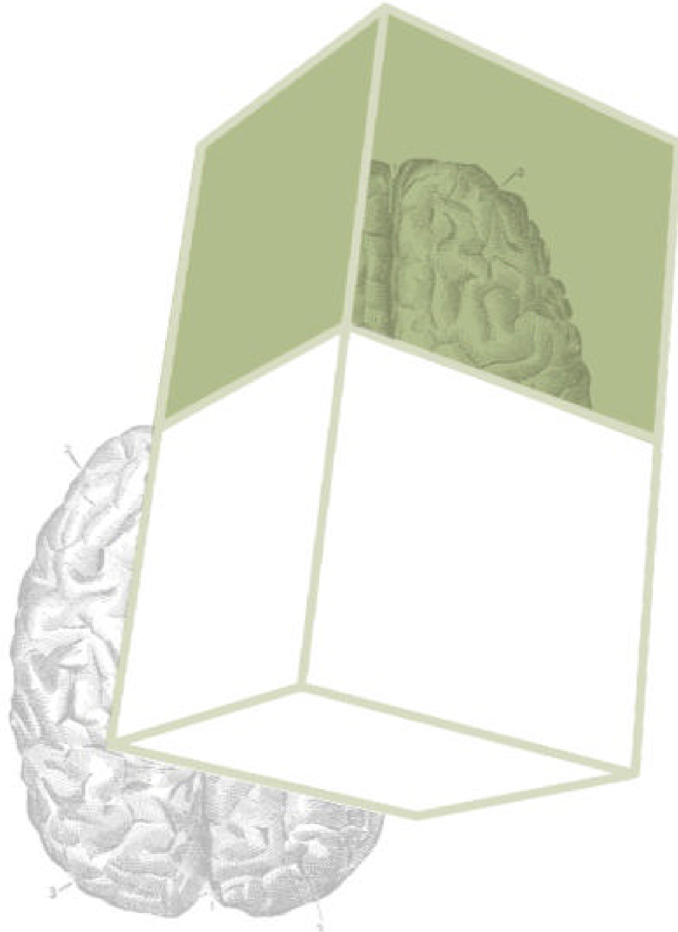
Those on the other side say the hard problem creates one where there is none: “It’s an unsolvable mystery, because the problem is ill posed,” says neuroscientist Michael Graziano of Princeton University: consciousness is nothing but a trick of the mind. What’s more, the brain doesn’t just create the illusion of consciousness, but also the feeling that there is a separate, immaterial “I” having a conscious experience. In other words, there is no need to explain strange interactions between material and immaterial things because the immaterial things don’t really exist.

For “materialists” such as Graziano, the real issue is not solving the hard problem, but explaining how the brain accomplishes this trickery. Graziano resolves this by saying that consciousness is “the brain’s way of describing to itself what it means to pay attention to and deeply process a signal”.

The argument goes like this: we must pay attention to our environment to survive. As a result, our brains have become very skilled at representing the world around us. Somewhere in the course of evolution, they began representing objects as having immaterial properties, and in so doing it generated the mirage of consciousness. Ultimately, most materialists take the view that after we die and our brains and bodies have decomposed, there is nothing left. That must mean that our prevailing sense of a separate, immaterial “I” is also an illusion.

Clues to how this all arises could come from studies of people with conditions like Cotard’s syndrome. In 2013, Adam Zeman at the University of Exeter, UK, and colleagues reported anomalies in brain scans in one such person. One was in a brain network associated with internal awareness, including the awareness of our body and its emotional state. Activity was down to levels normally seen in people who are minimally conscious. The researchers speculated that this created a perception of non-existence which the man could not discount because other parts of his brain responsible for rational thought were also damaged. The findings suggest that by creating a vivid perception of our body and its various states, our brain generates the feeling of existence – and any malfunction in this mechanism can cause us to question it.

How this all happens could be explained by the idea that the brain is a prediction machine. It is continually being assaulted by signals from the body and its environment and must predict what’s causing them. For example, when you are walking by the coast, the brain has to be able perceive that you are about to come to a cliff – if you don’t, you may fall off the edge. It does this by creating internal models of the body and the environment. To make accurate calculations, the brain must maintain prior knowledge and keep testing the integrity of its models. “The brain is a system that is continually trying to prove its own existence,” says philosopher Thomas Metzinger of the University of Mainz in Germany. But that’s a long way from saying that what we perceive is real. ▮



PERCEPTION VS REALITY

However our subjective conscious experience arises, it is obvious it can't tell us the whole story about reality. That starts with our limited sensory inputs. Humans, unlike bees, don't normally see ultraviolet light. We can't sense Earth's magnetic field, unlike turtles, worms and wolves. We are deaf to high and low pitches that other animals can hear, and we have a relatively weak sense of smell. Add in how our brains process information, and it become clear that our brains present us with a highly edited picture of the world.

DID you notice the last time you blinked? Are you conscious right now of that fleshy protuberance called your nose always in your peripheral vision? Only perhaps now because you've been made aware of them. Usually, our brains just edit these things out.

If our senses took in every detail of the world around us, we would be overwhelmed – so we get only a snapshot. "A lot of what our senses are doing is something like data compression: simplifying, in order to be able to function," says Mazviita Chirimuuta at the University of Pittsburgh in Pennsylvania.

In fact, most of what you "see" is an illusion. Our eyes aren't all-seeing, but capture fleeting glimpses of the outside world between rapid movements called saccades. During these, we are effectively blind because the brain doesn't process the information that comes in when they happen. If you doubt this, stare into your own eyes in a mirror, then rapidly flick your gaze from one side to the other and back again. Did you see your eyes move?

This is only the start of it. The brain, after all, is › sealed in darkness and silence within the solid casing of the skull. It has no direct access to the outside world, and so relies on the information that reaches it via a few electrical cables from our sensory organs. Our eyes pick up information about wavelengths of electromagnetic radiation, our ears detect vibrations of air particles and our noses and mouths detect volatile molecules that we experience as smells and flavours. Through complex processes we only partly understand, the brain integrates these independent inputs into a unified conscious awareness.

It is impossible to know anything about objective reality without also involving our processes of perception and thought. This is why some people think that there is no hard line between objective and subjective reality. "If you have this notion that reality is something that is inherently different from the mind, then it becomes paradoxical to think that we ever have access to reality," says Chirimuuta. "Reality depends on us, it depends on the way we see the world. But at the same time, what we're perceiving is one aspect of this reality because our perception is shaped by the senses we happen to have."

Take the colour blue. Physicists define it in terms of wavelengths of light – but the blueness you see isn't necessarily the same as the blueness anyone else sees. It isn't a property of the object, but a property of the interaction we have with it.

Other animals probably experience their own versions of reality. This logic also applies to the reality depicted by science. "The world described by physics is also like another interpretation based on measurements taken with scientific instruments that reveal properties and processes that the human senses can't, by themselves, latch on to," says Chirimuuta. ∎

SHARED REALITIES

Our conscious experience of reality may be nothing like the real thing, but at least we could hope we all share the same misrepresentation. All humans have roughly the same brains and sensory systems, after all, and when we talk about our conscious experiences we all seem to be on the same page. But again, evolution ensures this isn't the whole story – creating a back door through which all manner of odd perceptions slip in.


BORCHEE/ISTOCKPHOTO

THE only way you know you exist as a conscious being is experience of your own consciousness. The nature – and existence – of other people's consciousness is a closed book. For all you know, everyone else is a zombie.

Let's set philosophical solipsism to one side, however, and allow other people to have conscious experience. Do they all perceive the same events in the same way? The evidence suggests that they don't.

If you have ever watched a football match and felt incredulity at the referee's decisions, take comfort from the fact that the opposing fans feel the same – although for the opposite reasons. Both sets will end up feeling that they were on the wrong end of all the dodgy calls.

This, of course, isn't objectively possible, but since when did objectivity have anything to do with reality? "We perceive the world in relation to what we already believe," says Tali Sharot of University College London. This makes evolutionary sense because it allows us to create mental shortcuts. Evaluating every piece of new information would use up scarce mental resources. But the shortcuts open us up to many of the vices of the modern world, from fake news to conspiracy theories.

How is it that people can live in the same reality and yet experience it so differently? One obvious answer is that we are being lied to. Another is that we seek out or interpret facts to fit our pre-existing beliefs because of traits known as motivated reasoning and confirmation bias. Both are undoubtedly in play, but research on how our brains deal with information has revealed that something weirder is going on. It isn't merely a problem of interpretation, but of sensory perception itself. We literally see the world as we want it to be.

If you don't believe that, consider this experiment by Yuan Chang Leong, now at the University of California, Berkeley. He scanned people's brains while they viewed a series of images of faces merged with scenes. They had to decide whether an image contained more face or more scene and were paid for correct answers.

Leong also threw in an occasional curveball, offering to pay a bonus if the next image was more face, impose a penalty if it was more scene, or vice versa. Subjects reported seeing what they had been told would be more profitable. And it turned out that they weren't consciously fibbing for profit: activity patterns in the brain's visual cortex suggested that they were seeing what they said they were seeing.

This "motivated perception" isn't unique to vision. Other studies suggest smell, taste, reasoning and memory are influenced too. That seems strange, but again makes evolutionary sense. "The main goal of the perceptual system is to keep the brain alive, so you can pass on your genes," says Jay van Bavel at New York University. You might assume that this would favour authentic perception, and mostly it does – but not always. We are a social species and sometimes group identity, tribal cohesion and shared beliefs are more important than the truth. It's another reason why we don't always see the reality in front of us. Just ask a football fan.

DO WE MAKE REALITY?

While there may be various reasons why we do not always see the objective reality in front of us, the weirdness of quantum physics explored in chapter 4 seems to suggest another, unexpected perspective: that we play a mysterious part in constructing it. As so often with fuzzy quantum realities, however, whether you buy that is a matter of interpretation.

ANXO VIZCAÍNO

AT FIRST blush, to suggest that we create reality sounds like a combination of arrogance and absurdity. In what warped version of reality could reality only exist because of us? And yet if you spend any time pondering quantum theory, it is hard to escape the idea that the world becomes "real" only when we are looking at it. But does it?

The starting point for this question is the way quantum wave functions predict that objects such as electrons exist in a cloud of possibilities before measurement – yet we only ever see a definite reality. On measurement, an electron always assumes a single, definite position or state – something we would recognise as real.

←
Turn back to page 60 for more on the quantum wave function

That much is well-established, but the word "measured" is a weasel one. "Collapse happens on measurement, but 'measurement' is vague and anthropocentric and seemingly inappropriate to play a role in a fundamental description of reality," says Kelvin McQueen, a philosopher of quantum physics at Chapman University in California.

It's vague because it's often hard to say when a measurement takes place. Imagine, for example, replacing the background screen in the classic double-slit experiment used to demonstrate wave-particle duality with a photographic plate that you don't develop until later. When does the measurement happen – when the photons hit the screen, making the pattern, or when you develop it, revealing the pattern?

←
See page 62 for a fuller look at the double-slit experiment

One answer is to introduce conscious observation as the defining feature of measurement. But this raises some difficult questions, not least the nature of reality before conscious minds existed. Then there's the fact that consciousness is arguably no less vague a concept than measurement.

Integrated information theory (IIT) represents an attempt to solve the second objection by developing a mathematical measure of consciousness. It might also solve the first. IIT rejects the idea that consciousness is exclusive to humans and other complex organisms. Even inanimate objects may possess a rudimentary form of consciousness. Indeed, consciousness itself may be a fundamental property of matter. If so, then there was no such thing as a "pre-conscious" universe.

In any case, largely for want of a better alternative, it has been difficult to erase the conscious observer from quantum mechanics. If anything, subjectivity has recently begun to reassert its centrality in the making of objective reality. In quantum Bayesianism or QBism, a relatively new interpretation of quantum theory, wave function collapse is caused by observers updating their knowledge. There is no objective reality, only our subjective estimation of it.

But for Markus Müller at the University of Vienna in Austria, it doesn't go far enough. Müller is working on a model that suggests how an objective external world, including the laws of nature, can arise from subjective experiences.

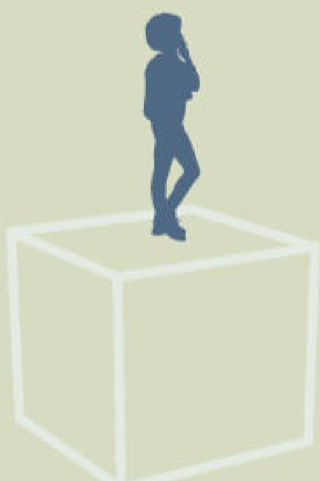
The idea is rooted in a probabilistic law used by AI researchers to help machines make predictions about the world by discovering regularities in the limited data they hold. In Müller's approach, this "algorithmic probability" is applied in reverse: it is not the world that is fundamental but the information and the probabilistic law, which happen to give observers the impression of a physical world with consistent laws of nature.

To the extent that Müller's ideas can be tested, the maths seems to work out, and his ideas have won praise as an unusually well-defined attempt to formulate a fundamental theory of reality from a first-person perspective."Müller's proposal is extremely interesting," says McQueen. "It effectively aims to resurrect an old idea in philosophy known as idealism, according to which experiences are not caused by a pre-existing physical reality but actually compose all the reality there is."

Einstein wouldn't have been so generous. When the founders of quantum mechanics first raised the notion that we make reality, he pointedly asked if the moon vanishes when you turn your back. He was, however, humble enough to admit he might be wrong. "One assumes a real world existing independently from any act of perception," he wrote in 1955. "But this we do not know." We still don't, but the idea that subjective reality is all there is has to be taken as a very real possibility. ▮

IS THERE MORE THAN ONE ME?

In the cold war US of the 1950s, a PhD student at Princeton University produced perhaps the most mind-boggling doctoral thesis of all time. Taking as his cue the mystery of what happens when we make a measurement of the quantum world, apparently turning its fuzziness into definite reality, Hugh Everett III proposed that the universe is constantly spawning parallel worlds. This quantum multiverse brings with it another peculiar question: could each of us have parallel multiple selves, each experiencing a different reality?



MULTIPLYING universes and selves might sound an implausible, not to mention profligate, way to solve any problem. But that's an aesthetic, not a scientific objection, and for adherents of the "many-worlds" interpretation of the quantum realm, this is serious science. David Deutsch at the University of Oxford, one of its most committed advocates, once began a talk at a meeting honouring Everett's work by saying, "I'll start with a simple fact: in this room, in some nearby universes, Hugh Everett is here with us, celebrating." Everett had in fact died several years earlier, in 1982 at the age of just 51 – at least in the branch of the quantum multiverse where we all ended up.

Lev Vaidman at Tel Aviv University in Israel is another physicist unequivocal that this sort of self-splitting really occurs whenever anyone measures the quantum world, "collapsing" its reality. "Based on what I know from physics, this is the only reasonable option," he says. "At the present moment, there are many different Levs in different worlds." He says his "I" corresponds not just to a particular Lev in the moment, but also to many Levs in the future.

In fact, Vaidman merrily creates his own Levs using his own free Many Worlds app which also uses a quantum optical measurement to make a decision with up to six outcomes for you. If you "have a strong will and fulfil what the device tells you, your parallel selves will fulfil the other options".

But there's a problem. If, in the many worlds, every possible outcome of a quantum measurement happens with 100 per cent certainty, what are those probabilities encoded in the quantum wave function which embodies reality before the measurement all about? This is the biggest stumbling block for Everett's idea: explaining why the quantum world looks fuzzy and probabilistic, if it is actually fully deterministic

“What does ‘I’ mean when worlds divide?”

because everything that can happen does.

In the late 1990s, Deutsch offered an explanation. Imagine you have the option of eating cake or pie, and would quite like both, just cake more. You could set up a quantum decider experiment to reflect your leanings – in the normal quantum formulation involving probabilities, with say 90 per cent chance of the “cake” outcome, and 10 per cent “pie”.

In the many-worlds formulation, you say that both branches are reached with 100 per cent probability, with what used to be probabilities becoming “branch weights”: essentially, how biased you have made the experiment towards or against a particular outcome. Deutsch showed that, if you know that each of your split selves will experience only one universe after the event, the only rational thing to do is to treat these branch weights as if they really are probabilities in the pre-split universe. “If Everett’s view is true, branch weight is an objective physical quantity with the right formal properties to be probability,” says David Wallace at the University of Southern California.

Not everyone is convinced. For one thing, this take seems to depend on saying that the apparent probabilities are nothing more than how we, if we are rational about it, ought to regard branch weights. An explanation that demands we assume a certain attitude towards the world doesn’t seem particularly compelling.

Vaidman advocates a different tack to overcome the many-worlds probability problem. His explanation is known as “self-locating uncertainty”. He illustrates it with a thought experiment. Imagine you agree to take a pill that puts you to sleep, and are placed in a room containing a chest. You know that, while you are asleep, someone else will perform a quantum experiment – fire a photon at a half-silvered mirror, say – and, according to the outcome, either place $1 million in the chest or nothing at all. In this scenario, when you wake up, it is perfectly reasonable for you to say before you look that there is a 50 per cent chance of the chest containing the fortune or not – a subjective probability that is set to be equal to the objective branching weight in the quantum experiment. In this scenario, apparent probability comes from the way that, after a quantum splitting, we are unsure which branch of the quantum multiverse we have ended up on.

Mateus Araújo at the Austrian Academy of Sciences is unsure this solves the problem, either. “Usually we talk about the probabilities of a future experiment, not one that has already been made,” he says. “If we’re thinking about probabilities of future outcomes, the question of which branch I will end up on doesn’t even make sense, because the notion of ‘I’ changes. You know that there will be future versions of you in all branches, all of which see a single outcome and remember being you now. There is no uncertainty.”

Behind all this talk about what probability means in the many-worlds interpretation lurks a more fundamental question: what does “I” mean when worlds divide? Any quantum interaction, anywhere in the universe, that ends up with a classical outcome – a protein channel in a brain cell contributing to a thought that becomes an action, for example – should split the universe. You yourself have split countless times while reading this – faster, indeed, than thought itself. There’s never a moment when you can be aware of a unique you.

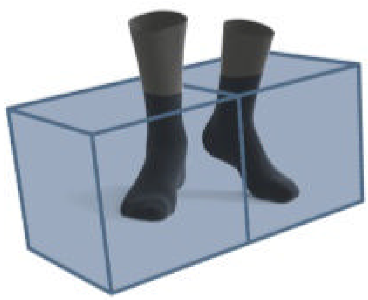
So in that sleeping-pill thought experiment, is the “I” that goes to sleep the same as the I that wakes up? If we are not defined by a unique thread of conscious awareness, how exactly are we defined? Many-worlders deny that identity is a problem, saying that the “I” is just a well-defined point in – or perhaps trajectory through – the branching multiverse.

But it isn’t easy to see what that means, if the branching is more fine-grained than thought. And it doesn’t do away with a fundamental problem – our apparent ability to shape reality in the way we make decisions.

THE MYSTERY OF AGENCY

What makes me decide to pull on that pair of socks in the morning and not another? It might seem a trite question, but it goes to the heart of a deep mystery about our relationship with external reality. We aren't passive participants in it, but active agents, changing it on the basis of our whims, experiences and predictions.

Choosing your socks might not change the world much, but other decisions do – and our deliberative power to do just that is, in terms of the physical laws we have uncovered so far, a complete enigma.



AT ITS simplest, agency is easy to define. "It is just the notion that certain systems in the world have intentional states, desires to bring stuff about," says philosopher Eleanor Knox at King's College London. "We're clearly systems like that."

The arguments start with what else is too. "Quantum fields don't have any agency. Atoms don't, do bacteria?" asks physicist Sean Carroll at the California Institute of Technology. "I don't know, but human beings do. Somewhere along that continuum it sneaked in."

Philosophers and theologians have been poring over that and agency's relationships to other thorny concepts, such as consciousness and free will, for millennia. But it is since humans started to do physics that agency has taken on particularly puzzling proportions.

The aim of physics is to characterise the interaction and evolution of all reality's elements through cast-iron mathematical laws. The mission is far from complete, but from Newton's laws of motion and gravitation to Einstein's relativity and the enigmatic edifice of quantum theory, such laws explain everything from how apples fall to how biological and chemical processes unfold to the origin of the universe.

←
Turn back to chapter 2 for more on the mathematical structure of reality

An apple's sudden detachment from a tree, for example, is caused by a complex series of biochemical processes, plus the whims of wind and weather, all explicable by the laws of physics. Given enough computational power, in theory we can trace the chain of causation back through Earth and cosmic history to the moment the carbon atoms within the apple were first manufactured in a supernova – and beyond that almost to the big bang and time's beginning.

But that apple was always going to fall; it can't choose to jump or decide not to fall. Agency is different. From a human perspective at least, our decision-making is discretionary; there is none of the inevitability that marks out physical laws. The chains of causation behind our actions are very complex, running through psychological influences brewed by nature, culture and nurture – and our current physical laws don't try to explain them.

That has been a popular way out for natural philosophers over the years, in various forms of mind-body dualism: the idea that the mental and physical realms are separate, and the rules of one don't apply to the other. But that hardly seems a tenable position within modern science. "Being a full-on dualist is quite hard because it does look like, for instance, when I put lots of serotonin in your brain, your mental states change," says Knox. "The question is how you think that could work if you think there's two kinds of separate stuff."

"If there's evidence we should carve out a different realm for organic things or people or whatever, then by all means," says Carroll. "But I'm made of atoms, my laws of physics purport to explain atoms, and it would seem by far the most likely hypothesis that the laws of physics explain me."

The central conundrum becomes what sort of physical laws can unify two very different, conflicting views: the fact that we seem in some degree to be agents free to make decisions on the basis of our mental states, and the fact that we are just bundles of atoms and molecules blindly following the laws of physics.

One popular explanation lies in emergence – the idea that behaviours and properties that are inscrutable when you look at single components of a complex system pop into existence when you view things as a whole. The temperature or density of a gas, for example, doesn't mean much at the level of single molecules. Look at all the molecules of the gas together, however, and they are measurable quantities that explain physical change: how temperature differences cause heat flows, for example, or how a gas pushes a piston when compressed. The trick in explaining agency might be to try to sidestep the complexities of the nearly 100 billion interconnected neurons within › our brains and their interactions, and focus instead on how the system as a whole works, and how that might fit into existing conceptions of physics.

One big clue is the way agency changes the future, but not the past. Most physical laws don't work like this: the basic equations of classical and quantum physics run just as well backwards as forwards. The only one-way street in physics is the inescapable rise of disorder, or entropy. This is encapsulated by the second law of thermodynamics, the empirical law that says ice creams melt, milk can't be unspilled and that it is far easier to lose one sock than to unite a pair.

← Find more on the mystery of time on page 41

Hidden away in thermodynamics is the concept of information. A century and a half ago, physicist James Clerk Maxwell imagined a tiny intelligent being that could gauge the speed of individual molecules in a gas to sort hotter ones from cooler ones, and so apparently decrease disorder and entropy in contravention of the second law. It's a fair bet that the essence of agency lies in an ability to harness, store and process different forms of information – from the past in the form of memories, for example, or in a much more limited way from the future in the form of predictions. Understanding agency, in some way, means understanding the ways reality regulates information flows.

That is a huge work in progress – and the fact that we have to use our minds to do all this work could yet be its undoing. "The question of how much of the structure that I see around me is my concepts projected onto the world, and how much is the world projected onto me, is one of the deepest in the philosophy of mind," says Knox. All we can say for certain about the laws of physics is that they make sense to us. Useful as their predictive power may be, we have no guarantee of their relationship to fundamental reality. It might be that physics has already extracted the easy stuff – the bits of the world amenable to characterisation by regular, mathematical laws – and put them in a box marked "physics". There's no guarantee that everything fits in there. Our agency might be fated to remain outside the reality we've invented. ▮

DOES FREE WILL EXIST?

It hardly seems in any doubt that we possess agency, even if the question of how our ability to change the reality around us fits in with the laws of physics remains a huge and open one.

Not so with a related quality that has been the subject of debate among philosophers since time immemorial: free will. To what extent are our decisions the product of our own desires, or just predetermined? Modern physics has given us some new ways of framing that question.

"OH, I am fortune's fool," says Romeo in *Romeo and Juliet*, having killed Tybalt and realising he must leave Verona or risk death. He was expressing a view common in Shakespeare's time: that we are all marionettes, with some higher cause pulling the strings of our destiny. Chance – let alone our own decision-making – plays little part in the unravelling of cosmic designs.

In this way of thinking, even processes that inherently involve chance are pre-determined. Long before dice were used for gaming, they were used for divination. Ancient thinkers thought the gods determined the outcome of a die roll; the apparent randomness resulted from our ignorance of divine intentions.

Oddly, modern science at first did little to change that view. Isaac Newton devised laws of motion and gravitation that connected everything in the cosmos with a mechanism run by a heavenly hand. The motion of the stars and planets followed the same strict laws as a cart pulled by a donkey. In this clockwork universe, every effect had a traceable cause. If you had all the relevant facts pertaining to a die roll at your fingertips – trajectory, speed, roughness of the surface and so on – you could, in theory, calculate which face would end up on top.

Confidence in cosmic predictability led the French mathematician and physicist Pierre-Simon de Laplace to assert, a century after Newton, that a sufficiently informed intelligence could forecast everything that is going to happen in the universe – and, working backwards, tell you everything that did happen, right back to the cosmic beginnings.

This sort of cosmic determinism is a glorious and rather discomfiting idea. If everything really is predictable, then surely free will is an illusion?

Experiments done by the neuroscientist Benjamin Libet in the 1980s certainly seem to give succour to the idea that we're not as much in control as we would perhaps like to believe. They showed mechanisms within the brain initiate actions long before that brain's owner is aware of deciding to perform them.

For Nicholas Humphrey, an emeritus psychologist at the London School of Economics, however, acknowledging that decisions have an involuntary, material cause in brain processes does not amount to denying free will. "On the contrary, I'm saying that I myself am the cause of it," he says. Humphrey calls his "I" an "embodied self": the sum of the thoughts, beliefs, desires, dispositions and so on that live within him. The embodied self might not be conscious of every action, but it ultimately determines them – a sort of free will on autopilot.

And anyway, drill down and it seems not everything is predetermined anyway. Scale up the randomness and uncertainty inherent in quantum physics, and what happens in the universe can't be entirely determined from beginning to end because you can never know what's going to happen at the smallest scales.

That doesn't give free will a free pass, however. The lesson of quantum theory is that we can't determine the result of any quantum process in advance – results will just happen according to the probabilities encoded in the quantum wave function describing whatever we're trying to find out, leaving us rather powerless. "Quantum mechanics doesn't insert us into the causal chain," says philosopher Jenann Ismael of Columbia University in New York. "It inserts uncontrollable events into the causal chain."

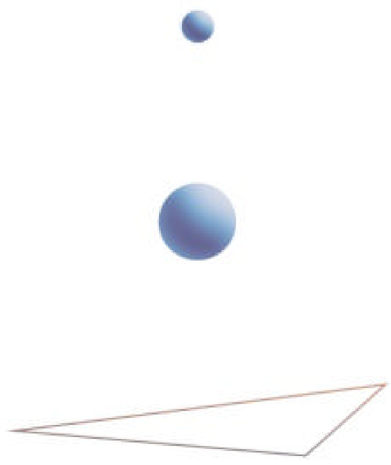
Unless, that is, you believe the many-worlds interpretation of quantum theory, which says that all this uncertainty is only because everything that can happen does happen, only in different universes. In this scenario, the universe really is predetermined. The only uncertainty lies in which pre-packaged universe you find your conscious self in – with all the problems that brings that have already been discussed.

The argument of Physics Nobel laureate Gerard 't Hooft that the universe is superdeterministic – that something outside it sets everything in stone, including the outcome of experiments we might do to test whether we have free will – takes things to an even further extreme. Fortune's fools? Perhaps we're not at liberty to decide. ▮

CHAPTER 6

IS ANYTHING ACTUALLY REAL?

We have looked at reality from many angles – its mathematical and physical basis, and the relationship between objective reality and our subjective perception of it. But implicit in most of our discussions is the idea that reality is somehow a "natural" construct, with laws we can uncover. Philosopher Nick Bostrom has advanced a very different idea – reality is made by us, or people like us. We are all living in a huge simulation.



SCIENCE has revealed much about the world and our position within it. Generally, the findings have been humbling. The Earth isn't the centre of the universe. Our species descended from brutes. We are made of the same stuff as mud. We are moved by neurophysiological signals and subject to a variety of biological, psychological and sociological influences over which we have limited control and little understanding.

One of our remaining sources of pride is technological progress. Like the polyps that over time create coral reefs, the many generations of humans that have come before us have built up a vast technological infrastructure. Our habitat is now largely one of human making. The fact of technological progress is also in a sense humbling. It suggests that the most advanced technology we have today is extremely limited and primitive compared with what our descendants will have.

If we extrapolate these expected technological advances, and think through some of their logical implications, we arrive at another humbling conclusion: the "simulation argument", which has caused some stir since I published it in 2003.

The formal version of the argument requires some probability theory, but the underlying idea can be grasped without mathematics. It starts with the assumption that future civilisations will have enough computing power and programming skills to be able to create what I call "ancestor simulations". These would be detailed simulations of the simulators' predecessors – detailed enough for the simulated minds to be conscious and have the same kinds of experiences we have. Think of an ancestor simulation as a very realistic virtual reality environment, but one where the brains inhabiting the world are themselves part of the simulation.

ANXO VIZCAÍNO

The simulation argument makes no assumption about how long it will take to develop this capacity. Some futurologists think it will happen within the next 50 years. But even if it takes 10 million years, it makes no difference to the argument.

Let me state what the conclusion of the argument is.It is that at least one of the following three propositions must be true:

→ **Almost all civilisations at our level of development become extinct before becoming technologically mature.**

→ **The fraction of technologically mature civilisations that are interested in creating ancestor simulations is almost zero.**

→ **You are almost certainly living in a computer simulation.**

How do we reach this conclusion? Suppose first that the first proposition is false. Then a significant fraction of civilisations at our level of development eventually become technologically mature. Suppose, too, that the second proposition is false. Then a significant fraction of these civilisations run ancestor simulations. Therefore, if both one and two are false, there will be simulated minds like ours. ›

PROFILE
NICK BOSTROM

Nick Bostrom is a philosopher and founder of the Future of Humanity Institute at the University of Oxford. He has worked extensively on existential risks and technological progress, and is the author of the book *Superintelligence: Paths, dangers, strategies*

If we work out the numbers, we find that there would be vastly many more simulated minds than non-simulated minds. We assume that technologically mature civilisations would have access to enormous amounts of computing power.

So enormous, in fact, that by devoting even a tiny fraction to ancestor simulations, they would be able to implement billions of simulations, each containing as many people as have ever existed. In other words, almost all minds like yours would be simulated. Therefore, by a very weak principle of indifference, you would have to assume that you are probably one of these simulated minds rather than one of the ones that aren't simulated.

Hence, if you think that propositions one and two are both false, you should accept the third. It is not coherent to reject all three.

It should be emphasised that the simulation argument does not show that you are living in a simulation. The conclusion is simply that at least one of the three propositions is true. It does not tell us which.

In reality, we don't have much specific information to tell us which of the three propositions might be true. In this situation, it might be reasonable to distribute our credence roughly evenly between them.

Let us consider the options in a little more detail. Proposition one is straightforward. For example, maybe there is some technology that every advanced civilisation eventually develops and which then destroys them. Let us hope this is not the case.

Proposition two requires that there is a strong convergence among all advanced civilisations, such that almost none of them are interested in running ancestor simulations. One can imagine various reasons that may lead civilisations to make this choice. Yet for proposition two to be true, virtually all civilisations would have to refrain. If this were true, it would be an interesting constraint on the future evolution of intelligent life.

The third possibility is philosophically the most intriguing. If it is correct, you are almost certainly living in a computer simulation that was created by some advanced civilisation. What Copernicus and Darwin and latter-day scientists have been discovering are the laws and workings of the simulated reality.

These laws might or might not be identical to those operating at the more fundamental level of reality where the computer that is running our simulation exists (which, of course, may itself be a simulation). In a way, our place in the world would be even humbler than we thought.

What kind of implications would this have? How should it change the way you live your life?

Your first reaction might be to think that if three is true, then all bets are off and you would go crazy. To reason thus would be an error. Even if we are in a simulation, the best methods of predicting what will happen next are still the familiar ones – extrapolation of past trends, scientific modelling and common sense. To a first approximation, if you thought you were in a simulation, you should get on with your life in much the same way as if you were convinced that you were leading a non-simulated life at the "bottom" level of reality.

If we are in a simulation, could we ever know for certain? If the simulators don't want us to find out, we probably never will. But if they choose to reveal themselves, they could do so. Another event that would let us conclude with a high degree of confidence that we are in a simulation is if we ever reach a point when we are about to switch on our own ancestor simulations. That would be very strong evidence against the first two propositions, leaving us only with the third. Welcome to reality.

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