How to think about...

SCIENCE is our best route to understanding an otherwise unfathomable universe. And yet the path to enlightenment is far from straight and smooth. It throws up all manner of concepts to help us make sense of things that can appear to not make much sense at all – and then chucks in a bunch of fresh discoveries that force us to reconsider those concepts. That's what makes it so much fun. But even for the curious and well-informed, it can be hard to get to grips with some of the most nebulous, controversial and mind-boggling ideas.

Which is why, over the next 11 pages, we are going to clear a few things up by asking the experts how they think about 12 of the trickiest concepts in science and technology, from neurodiversity and fractals to artificial general intelligence and quantum biology – and even thought itself.

How to think about...How to think about...How to think about...Ho


STEPAN POPOV/STOCK.ADOBE

THOUGHT

WE'RE ALL AT IT, all the time. Yet thinking, or how we should think about thought, is surprisingly hard to pin down. When I did a vox pop, for instance, a couple of friends described thoughts as "wispy things". Another saw them as sparklers, fizzing with chaotic flashes but containing a central light source that is controllable.

All of which is decidedly unscientific. But then even the experts aren't so sure about what thoughts are, and what we can surmise from the latest neuroimaging studies suggests we may never truly pin down how they manifest in the brain.

"The short answer is that no one really knows what thought is," says Tim Bayne, a philosopher at Monash University in Australia and author of *Thought: A very short introduction*. Even so, it is useful to consider two aspects of thought, he says: their content and their nature.

Kalina Christoff's definition does exactly that. "Thought is a mental state, or series of mental states, that has some kind of content to it, with some personal attitudes towards the content – like an attitude of remembering or believing or imagining," says Christoff, who runs the Cognitive Neuroscience of Thought Laboratory at the University of British Columbia in Canada.

First, let's consider content. Thinking isn't the same as perceiving or sensing: all involve holding something before one's mind, so to speak, but thoughts are distinct in that they are independent of any stimulus produced by the thing being thought about.

In terms of how they arise, Christoff identifies three streams that feed into our consciousness to instigate thoughts: exteroceptive (from the outside world), interoceptive (from your organs and internal physiological environment) and conceptive (a term she uses to describe input that "wells up" from the subconscious in the form of spontaneous thought, including mind wandering or daydreaming, as opposed to intentional thought such as reasoning and problem-solving).

Within content, there is form. There are five main kinds of thought, according to Russell Hurlburt at the University of Nevada, Las Vegas, who invented "thought sampling", in which volunteers record their current inner experience when prompted randomly by a beeper. This process reveals that a thought can be verbal, visual, emotional, founded in bodily sensations or unsymbolised (none of the above, yet still distinct) – or a mixture of these. There is enormous variation between individuals in terms of how they think, says Hurlburt, even if many of us fail to recognise this (see "Neurodiversity", page 39).

As for the nature of thought, or what thoughts look like in the brain, Christoff uses functional magnetic resonance imaging to explore this. "For sure there are neural correlates," she says. Some of the brain activity simply reflects the kind of thought being had – for example, a visual thought will show activation in the visual cortex. More surprising is what happens prior to spontaneous thought: about 3 seconds beforehand, there is activity in parts of the default mode network, which generally fires up when your brain is idling, and also in brain regions associated with memory. The latter have unusually diverse connections, which might help explain why spontaneous thoughts are so eclectic and arbitrary.

> "WE MAY NEVER TRULY PIN DOWN HOW THOUGHTS MANIFEST IN THE BRAIN"

Neuroimaging can give us a general idea of what someone is thinking, then. But Christoff doesn't believe it will ever accurately interpret the subjective experience of thinking and thus make it possible to read people's minds – something that has been touted as a goal for the brain-computer interfaces being pursued by Elon Musk's Neuralink, among other companies. "The mind emerges out of a physical substrate, the brain, and the relationship of emergence is not deterministic," she says.

Kate Douglas

ROGUE PLANETS

IMAGINE A WORLD where it is always night, no matter the time of day or year. There are no days or years, in fact, because there is no sun, meaning no cycle of daylight to mark time's passing. And if there are moons, they are barely visible. For this is a lonely world, drifting through interstellar space.

Rogue planets, as they are known, do exist – and there are probably a lot of them. They could outnumber stars by up to 20 times, according to a 2023 analysis by David Bennett at NASA's Goddard Space Flight Center in Maryland and his colleagues, which would mean there are possibly trillions of them in our galaxy alone.

That might sound like an outlandishly large number, given that we tend to think of planets orbiting stars. But the existence of free-floating planets is perfectly compatible with planetary formation theory. "Honestly, I was not surprised to find that rogue planets may outnumber stars," says Gavin Coleman at Queen Mary University of London.

Which isn't to say astronomers aren't awestruck by the prospect. "It's beautiful to imagine," says Lisa Kaltenegger at Cornell University in Ithaca, New York. "Billions of planets that have no home any more, that are just basically travelling through the galaxy."

We can't see rogue planets directly. Since the first candidate was discovered in 2012, we have been inferring their presence by the way they bend the light coming from more distant stars and galaxies, known as gravitational microlensing. From this, it appears as if most rogue planets are around the size of Earth.

Those that are larger could start life in a similar way to a star, with clouds of gas gathering under gravity and eventually collapsing. But this can't account for Earth-sized rogue planets, says Coleman – those must have formed within a solar system and then been ejected. An outside star might have swept by, tugging on the planet as it went, but this is only likely in star-dense regions of the galaxy, like globular clusters. Another option is that a tussle with another planet in the system flung one closer to the star and one away, out into the wilds.

The most likely explanation for rogue planets in the Milky Way is that they formed around pairs of stars orbiting each other, called binary systems. "In binary systems, it is very easy for planets to be placed on orbits that eventually lead to their ejection," says Coleman.

As for the conditions on rogue planets, we can expect the same rich diversity we see in star-bound planets – from smaller rocky worlds to massive gas giants like Jupiter and icy exoplanets bigger than Neptune. "I imagine that rogue planets will be very similar to a lot of these," says Coleman. Except for the fact that, with no host star for light, the only source of warmth will have to come from within. As such, it is likely that rogue planets will have frozen surfaces.

> "THERE COULD BE TRILLIONS OF THESE LONELY WORLDS IN OUR GALAXY ALONE"

One source of energy could come from thermal vents powered by the contraction of the entire planet as it cools down, the mechanism that leads to cryovolcanism on Pluto. But there are ways such a rogue planet could be warmer than this. David Stevenson at the California Institute of Technology, Pasadena, has argued that if they had large amounts of hydrogen in their atmospheres, which is a greenhouse gas at high pressures, rogue planets could even have surface temperatures similar to those on Earth. "Such a planet could be kept warm by the radioactive decays of elements deep in its interior," says Bennett.

Simulations have even suggested that some rogue planets might have what it takes to be habitable, either in liquid oceans beneath their icy outer crusts or on the surface if they can sustain a thick hydrogen atmosphere to trap enough heat to sustain life.

Abigail Beall

SHUTTERSTOCK/ARTSIOM P

Rogue planets are likely to be frozen worlds

SUNNY/GETTY IMAGES

Dropping the cup leads to it smashing – or does it?

CAUSALITY

YOU DROP A CUP and it smashes. I flick a light switch and the bulb glows. Effect follows cause – it is a hard-and-fast rule of the universe. Except, perhaps, at a fundamental level. Because when we are dealing with the electrons behind the working of the light switch and the atoms in the bulb that convert electrical energy to light, causality appears to be a lot fuzzier.

In 2017, a team at the University of Vienna in Austria described an experiment demonstrating that, in the quantum realm of atoms and particles, it is impossible to say which observations were the effect and which were the cause. It was, in the words of the researchers who did the experiment, "the first decisive demonstration of a process with an indefinite causal order".

And yet the wider research community didn't drop their coffee mugs. On the contrary, it was welcome news for at least some of those seeking to figure out where space-time comes from. For them, a quantum theory of gravity, in which space-time would be an emergent property of more fundamental constituents of the universe, might necessarily lack the definite one-way causality of everyday life.

Space-time, as described by Albert Einstein's theories of relativity, already has some fuzziness when it comes to defining the order of events. People moving through space and time in different ways have different "reference frames", and those moving in different ways won't always agree on whether event A happened before event B.

This doesn't allow breaches of causality, though. The blurring of before and after happens only over distances so large that those regions of space can't affect each other because of the limit on the speed of light. "If one event could send a light signal to the other, then there is no reference frame in which you could confuse their order," says Giulia Rubino, now at the University of Bristol, UK, who led the 2017 work.

However, "indefinite causality" is possible in the minuscule quantum world because the rules that govern the behaviour of atoms, electrons and photons of light permit a phenomenon called "superposition". This is where a system of such entities can exist in two or more states simultaneously – even if common sense would say that it is impossible for those states to co-exist. Thus the 2017 experiment involves creating a superposition of "A causes B" and "B causes A" when dealing with photons, or particles of light, that are themselves in superposition.

That isn't discombobulating for physicists because the fundamental laws of quantum physics don't specify a direction for time, says Huw Price at the University of Cambridge: "Physics doesn't care about the difference between past and future."

Hence, there is scope for "time-reversal symmetry", where particles behave in the same way if you make time run in the opposite direction. Nor do physicists rule out the possibility of backwards causation, or "retrocausality", in which a light bulb's glow could cause its switch to turn on.

The reason why some theorists embrace indefinite causality is that if space-time is fundamentally quantum mechanical – as many think it must be – then gravity must somehow be quantum mechanical too. To figure out what this quantum gravity looks like, Lucien Hardy at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, has suggested combining the characteristic features of general relativity and quantum mechanics: the malleability of space and time and superpositions of simultaneous possibilities, respectively. If you do that, he reasons, conventional notions of fixed time and causality must go.

"It seems that some situations, such as indefinite causal order, should be natural in quantum gravity," says Caslav Brukner at the Institute for Quantum Optics and Quantum Information in Vienna.

Michael Brooks

> "TO FIGURE OUT QUANTUM GRAVITY, CONVENTIONAL NOTIONS OF FIXED TIME AND CAUSALITY MUST GO"

BIODIVERSITY

AT FIRST BLUSH, the idea of biodiversity seems simple enough. It is essentially the variety of all life on Earth. But making sense of biodiversity in a way that can help us halt or even reverse its decline is anything but straightforward.

"People often use the word biodiversity just to mean any characteristic of life out there that we might care to protect," says Mark Vellend, a biologist at the University of Sherbrooke in Quebec, Canada. "That's not a definition I find useful in science because if it's everything, it's nothing."

For biodiversity to be a valuable concept, he says, it needs to be a measure of biological variety. That way, we can not only assess where we are and where we are headed, but also how best to conserve the biodiversity we have left.

The problem is that variety itself comes in many forms, especially in biology. "You can't just come up with a single number for biodiversity in the same way as you can for carbon," says Andy Hector at the University of Oxford. "It's way, way more complicated."

We already have ways to measure biodiversity. That's how we know it is in steep decline. They boil down to what biologists think of as dimensions of biodiversity. One of the most basic is species richness, which is simply the number of species in a given place at a given time. This has been used extensively and can sometimes be a useful proxy for other dimensions of biodiversity, says Hector.

One of those is the relative abundance of the different species. Two ecosystems can be equally rich in species, but not in diversity. "The way I like to explain it is if you walk through a forest or swim through a coral reef and you see two organisms in sequence, what are the odds that they're going to be different things?" says Vellend. "You could have a thousand types of things in there, but if 99 per cent of them are of one type, then the odds are, when you see two in a row, it's going to be the same thing."

A third dimension is how different the species are from one another in some important aspect. "Functional diversity", for example, looks at the range of different roles that species play in an ecosystem, such as in photosynthesis, nutrient recycling, predation or pollination.

But there is also a fourth dimension, which tracks how the other three change over time. Every measure of biodiversity worth its salt captures one or more of these aspects, weighted according to what data is available and the project's goals. "It all depends what you want," says Hector. "Are you trying to conserve biodiversity for biodiversity's sake or is it more human-centric?"

> "YOU CAN'T JUST COME UP WITH A SINGLE NUMBER FOR BIODIVERSITY IN THE SAME WAY AS YOU CAN FOR CARBON"

And here's where things get knotty, because there are myriad ways of measuring each dimension. That means the whole thing risks becoming frighteningly fractal (see "Fractals", page 39) – and indeed fractious. When discussions started on how to define the 2020 global biodiversity targets, there were nearly 100 suggestions on the table, according to Henrique Pereira at the University of Halle-Wittenberg in Germany.

In 2013, researchers led by Pereira began trying to standardise the way biodiversity is measured. They distilled biodiversity to six key dimensions: genetic composition, species distribution and abundance, species traits, community composition, ecosystem functioning and ecosystem structure. These capture the essence of biodiversity and how it is changing in a format that biologists can measure and share, says Pereira.

Not everyone is on board. But there is at least a growing realisation that the time for such quibbling has long passed. There isn't, and probably never will be, a comprehensive measure of biodiversity, says Hector. And ultimately, "we don't have the luxury of waiting until all life is documented", he says.

Graham Lawton

HANS-JOACHIM SCHNEIDER/ALAMY

Biodiversity contains several dimensions

QUANTUM BIOLOGY

"I'M NOT SAYING it's all true," says Christoph Simon, a physicist at the University of Calgary in Canada. "I'm just saying it is not crazy to look for it." He is talking about the possibility that life has found ways to make use of quantum effects in a host of essential phenomena, from photosynthesis and the navigational abilities of birds to consciousness.

The idea has long been seen as a bit fringe, on the assumption that such fragile effects must quickly disappear in the warm, wet environment of cells. Quantumness tends to prosper in very cold systems that are carefully isolated rather than part of a tepid soup awash with other activity.

But that is beginning to change, with tentative evidence for quantum behaviours in the machinery of cells and hints that quantum biology may not play by the conventional rules governing the subatomic world, raising new questions about the boundary between the classical and quantum realms.

"You could say, 'well, all molecules are quantum mechanical, so everything in biology is quantum mechanical'," says Greg Scholes, a chemist at Princeton University. But the idea of quantum biology only really gets interesting, he says, with the possibility that it explains emergent macroscopic behaviour that can't be predicted using classical laws.

Finding such behaviour typically means searching for evidence of archetypal quantum traits such as superposition, in which a system appears to exist in multiple states simultaneously before it loses this so-called quantum coherence and "collapses" into one state or another – a process called decoherence.

Hints of superposition have been observed in proteins called microtubules in cells in vitro, for example, but so far all these results are only "correlative", says Clarice Aiello, who leads the Quantum Biology Tech (QuBiT) Lab at the University of California, Los Angeles. That is because we haven't pinpointed how microscopic quantum behaviour might produce macroscopic consequences. "No one has unambiguously proven or refuted whether quantumness survives inside cells for long enough for it to matter," says Aiello.

She has a few ideas about how that might happen, though. Her research focuses on the surprising effect that magnetic fields have on a host of biological processes – from cell metabolism to DNA repair. "The whole machinery of cells might be responding to weak magnetic fields," she says. The idea is that these fields influence a quantum property of electrons called spin, which is relatively resilient to loss of quantumness, with knock-on effects for the chemical products that form downstream in biochemical processes. "The macroscopic consequences would be felt for much longer than the quantumness," says Aiello.

Scholes, meanwhile, is building a new theoretical framework to tell us where – and how – to look for quantum effects in biology. His take-home message is that the usual quantum rule book, based on interactions between small numbers of particles, doesn't apply. "We need to embrace [quantum biology's] complexity," he says. "Somehow, we need to develop a new kind of language."

Broadly, coherence is characterised by the extent to which different waves are in step with each other, known as their phase, so Scholes began to look for an equivalent in biology. He borrows the mathematics of graph theory, which describes the relations between large numbers of objects, adding up biological oscillations to identify an emerging pattern of phases. Scholes says that oscillations occur in living organisms, including in biochemical process inside cells and across networks of neurons in the brain. He suggests they could be behind some of the hints of quantum effects seen in experiments.

Scholes's ideas have also begun to blur the boundary between what we think of as quantum and classical. Although these biological states are akin to quantum superposition, all of his calculations were done using classical laws of nature. For this reason, Scholes calls them "quantum-like" states.

He has even started to speculate about what these quantum-like states might be doing inside brains: "They could bring information from different regions together quickly and efficiently, to give a leap of intuition, or a moment of recognition."

Thomas Lewton

AGI

IF YOU TAKE EVEN a passing interest in artificial intelligence, you will inevitably have come across the notion of artificial general intelligence. AGI, as it is often known, has ascended to buzzword status over the past few years as AI has exploded into the public consciousness on the back of the success of large language models (LLMs), a form of AI that powers chatbots such as ChatGPT.

That is largely because AGI has become a lodestar for the companies at the vanguard of this type of technology. ChatGPT creator OpenAI, for example, states that its mission is "to ensure that artificial general intelligence benefits all of humanity". Governments, too, have become obsessed with the opportunities › to think

AGI might present, as well as possible existential threats, while the media (including this magazine, naturally) report on claims that we have already seen "sparks of AGI" in LLM systems.

Despite all this, it isn't always clear what AGI really means. Indeed, that is the subject of heated debate in the AI community, with some insisting it is a useful goal and others that it is a meaningless figment that betrays a misunderstanding of the nature of intelligence – and our prospects for replicating it in machines. "It's not really a scientific concept," says Melanie Mitchell at the Santa Fe Institute in New Mexico.

Artificial human-like intelligence and superintelligent AI have been staples of science fiction for centuries. But the term AGI took off around 20 years ago when it was used by the computer scientist Ben Goertzel and Shane Legg, cofounder of the AI firm DeepMind. The phrase neatly encapsulated the growing sense that the field should move beyond narrow applications to build systems that can do everything a human can do.

Since then, DeepMind in particular has sought to redefine AGI such that it pertains only to "cognitive tasks". Last year, Legg, together with DeepMind cofounder Demis Hassabis and their colleagues, elaborated on what constitutes an AGI. They proposed a six-level framework, where the top level is a system that can "outperform 100 per cent of humans" across a "wide range of non-physical tasks, including metacognitive abilities like learning new skills".

"The levels idea is really pointing out that there's this continuum," says team member Meredith Morris at DeepMind, now part of Google. "There's this progression as technology evolves." Morris hopes their work will draw more attention to the idea, and ultimately to some form of consensus on what AGI actually is: "We would love to have folks from those other fields that study intelligence and learning working together with our researchers on developing these benchmarks."

But Mitchell points out that intelligence is itself a multidimensional concept, with a lot of crossovers with other equally murky concepts, such as sentience and understanding. As such, it isn't readily measurable with a test in the same way as other, more concrete tasks, like the ability to translate language.

Applying more scrutiny to when an AI could be considered an AGI might yield progress, but Mitchell is still sceptical that the sort of machine that AGI proponents envisage will be achieved, because it is unclear whether the faculties of human intelligence can ever be abstracted into standalone concepts – never mind replicated in AI. "There's a kind of faith that the field has had for a long time, that we can develop human-level intelligence in these disembodied substrates," she says. "Whether that's possible or not, I think it's a big open question."

> "SOME ARGUE THAT AGI IS A MEANINGLESS FIGMENT THAT BETRAYS A MISUNDERSTANDING OF THE NATURE OF INTELLIGENCE"

For Thomas Dietterich at Oregon State University, the problem with AGI is a more practical one – namely that it is a mistake to define artificial intelligence with respect to humans. "We have this focus on replicating our capabilities, and this leads to the rampant anthropomorphisation of our systems, giving them names like Siri and Alexa."

Instead, he says, we should think of AI as "an intelligence prosthetic that can do certain things for us" – which sounds a lot like what the AI community had in mind before the concept of AGI came along.

Alex Wilkins

YOU HAVE ALMOST certainly seen computer-generated fractals – beautiful, trippy images in which colourful, intricate structures repeat ad infinitum as you fall ever further down the rabbit hole. Formally speaking, fractals are infinitely complex patterns that are self-similar across different scales. But, in an echo of their geometry, fractals can help us better understand the world on many levels.

Let's start with the familiar: fractals in nature. "They are all around us – in trees, mountain ranges, river deltas and so on," says Dave Feldman at the College of the Atlantic in Bar Harbour, Maine. Such ubiquity makes sense because of the way fractals are made:

Fractal geometry is common in nature

SHUTTERSTOCK/SABINE HORTEBUSCH

FRACTALS

"a simple iterative process – repeated folding or branching – can produce fractals", he says.

These forms aren't just for gawping at, though. The inside of your lungs is fractal for a reason: such arrangements cram a huge surface area into a small volume of space. This is how evolution solved the problem of maximising the area of tissue that can absorb oxygen.

Where fractals get baffling, however, is in the reasons they captivate mathematicians, not least as a playground for exploring numbers. This is where we encounter fractal dimensions. In our everyday world, a straight line is one-dimensional, a square or rectangle two-dimensional and a cube or sphere three-dimensional. But fractal structures have dimensions in between these values. Though largely impossible to visualise, you can think of these as a measure of how much complexity a fractal contains – or how many self-similar structures you can break it into at a given magnification.

These kinds of measures can matter. As a coastline changes over time, so too does its fractal dimension, which can give a measure of the effect of sea level rise, while the fractal properties revealed by MRI scans can help doctors diagnose various diseases. "Lung disease is often a disturbance in the fractal complexity of the lungs, and Alzheimer's degrades the fractal complexity of neurons," says Peggy Beauregard at Hartford University in Connecticut.

Fractals also help us make sense of weather, climate and other "chaotic" systems – those that develop along wildly different paths through a map of all their possible states in response to the tiniest change in initial conditions. The connection with fractals is that the map of these paths, known as an "attractor", often has a fractal structure.

Hidden fractal structures might even transform our understanding of fundamental physics, according to Tim Palmer at the University of Oxford. He has developed a way of describing the laws of physics in terms of fractal geometry, where all the possible states of the universe are represented by an attractor, an arrangement that precludes some states from ever being reachable.

That would explain away the weirdness of quantum "entanglement", says Palmer, where two or more particles affect each other in ways that defy common sense (see "Quantum entanglement", page 41). He says entanglement is an illusion created by imagining that the universe can move between any and all possible states, when in reality it can't.

But Palmer goes further, proposing that rethinking all of physics based on fractal geometry could show how the small and large-scale properties of the universe are interconnected (see "Scale", page 43). "The laws of physics are much more holistic than we think," he says.

MB

NEURO-DIVERSITY

AS A CHILD, I was frequently scolded for zoning out in class, interrupting conversations and losing just about everything I owned. It wasn't until adulthood, when I was diagnosed with ADHD, that these "bad habits" began to make sense.

The idea that my brain is wired differently is the foundation of neurodiversity, a relatively new framework for understanding neurodevelopmental conditions like ADHD and autism. "Neurodiversity reflects an awareness that, across humanity, we have many different ways of perceiving and relating to the world that reflect differences in our brain development and brain function," says Geraldine Dawson at Duke University in North Carolina.

Instead of viewing these differences as problems to be fixed, a neurodiverse approach aims to embrace them, she says.

That seems clear enough. But the concept of neurodiversity has been a source of debate in recent years, particularly in terms of what it means for psychiatrists and neuroscientists, who have long thought in terms of neurodevelopmental "disorders", and the people they are seeking to help.

"Some people take it that the neurodiversity paradigm is against the medical paradigm," says Anita Thapar, a psychiatrist at Cardiff University in the UK. "What I have argued in several papers is that both are useful for difference purposes."

To start from the beginning, the term "neurodiverse" was first coined in the late 1990s by sociologist Judy Singer, who used it when describing › people with autism who had no intellectual impairments but struggled with relating to others or had repetitive behaviours.

The idea was to view autism as a difference, rather than as a disease or disorder, says Thapar. It also emphasised the many strengths that can come with autism, such as high levels of creativity, an intense focus on special interests or out-of-the-box thinking.

And it seems to have brought positive outcomes, by encouraging people to view their condition in a more positive light. Research shows, for example, that taking a strengths-based approach to autism improves social engagement, learning and self-advocacy and reduces anxiety.

"The strengths-based model is not about solving all problems, it is about helping people on the [autism] spectrum so that they are going to be able to have opportunities just like everyone else," says Lawrence Fung at Stanford University in California.

> "EMBRACING NEURODIVERSITY NEEDN'T MEAN ABANDONING DIAGNOSIS AND INTERVENTION"

Which brings us to a key point, and one that is commonly misunderstood – namely that neurodiversity isn't meant to minimise the fact that autism comes with real challenges, says Dawson. Rather, it focuses on reducing those difficulties with interventions that allow for agency and choice, she says.

Over the years, the concept has expanded to encompass the entire autism spectrum, as well as other neurodevelopmental conditions like ADHD, learning disabilities and dyslexia. Some have taken it even further, suggesting that people with mental health conditions like anxiety, depression and schizophrenia are also neurodiverse – or even that we are all neurodiverse, in the sense that no two brains are the same.

This is where the waters get muddy. "From a research perspective, we have never been able to draw a firm line between what is neurotypical and what is neurodiverse," says Dawson. But that presents a problem, says Thapar. "I think to call everything neurodiverse becomes meaningless."

For her, "neurodiverse generally means those with early neurological brain differences". In other words, neurodevelopmental conditions. And Thapar is clear that embracing neurodiversity needn't mean abandoning diagnosis and intervention altogether. The trick is to pay attention to the extent to which a person's neurodevelopmental difference is causing them problems, as well as their wants.

"You need to have that flexibility," she says. "When I'm seeing someone in clinic, I'm not just thinking about their brain, I'm thinking about them. I'm thinking about them as a person."

Grace Wade

BJANKA KADIC/ALAMY

NET ZERO

A DECADE AGO, the term "net zero" was arcane jargon. Today, it is the key goal of the fight against climate change and a familiar talking point across the world.

The concept is straightforward. In the words of the Intergovernmental Panel on Climate Change (IPCC): "Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period."

It is also easy to trace the concept's rise to prominence. Once the need for net-zero emissions to halt rising temperatures was established, it made its policy debut in the 2015 Paris Agreement. It then exploded into public consciousness following a 2018 IPCC report explicitly stating that the world must reach net zero by 2050 to avoid the worst effects of global warming. The UK soon became the first major economy to come up with a net-zero emissions pledge. Now, most countries, including China, the US and India – the three largest emitters – have made such pledges of some sort.

What is less clear, however, is whether all these targets are strong enough to get us to net zero fast enough – and what happens to the climate once we do reach our goal.

Many net-zero pledges are "poor", according to the Climate Action Tracker project. Often countries' plans lack achievable interim steps or leave out important sectors of the economy. That suggests most deadlines will be missed. But reaching net zero 50 years from now, for instance, isn't enough, says Amanda Levin at the Natural Resources Defense Council. "You have to make efforts to cut carbon today."

What's more, achieving net-zero emissions is just one of several important goalposts on which the future climate depends. How much we emit before reaching net zero and what happens after we get there are equally important, says Levin.

Another issue lies in how emitters can claim to be making progress by paying for others to avoid emissions – for instance by protecting a forest that would otherwise be cut down – rather than reducing their emissions. While such "carbon offsets" work in theory, in practice they are often difficult to verify, says Levin. "The offset market today is highly unregulated and, honestly, a Wild West."

Besides, offsetting based on avoided emissions will grow ever scarcer as we run out of emissions to avoid, so it can't be part of the long-term solution, says Myles Allen at the University of Oxford. "Because it's been abused, the environmental community is now fed up with it." As a result, some have called for commitments to "real zero," as in no emissions whatsoever. But emissions from long-distance flights or fertiliser use, for instance, are nigh-on impossible to eliminate, says Levin. Hence the push for CO_2 removal through technologies like direct air capture or other, nature-based approaches.

As for what will happen if the world does reach net-zero emissions on time, one recent study found that warming feedbacks could mean temperatures continue rising, depending on how much we emit overall. In that case, even more carbon removals would be needed to both address the overshoot and maintain net zero as natural sinks begin to bring down the atmospheric concentration of CO_2. "The real balance we need in the long term is between producing carbon dioxide and permanently disposing of it," says Allen.

James Dinneen

QUANTUM ENTANGLEMENT

WHILE SCIENTISTS generally try to find sensible explanations for weird phenomena, quantum entanglement has them tied in knots.

This link between subatomic particles, in which they appear to instantly influence one another no matter how far apart, defies our understanding of space and time. It famously confounded Albert Einstein, who dubbed it "spooky action at a distance". And it continues to be a source of mystery today. "These quantum correlations seem to appear somehow from outside spacetime, in the sense that there is no story in space and time that explains them," says Nicolas Gisin at the University of Geneva, Switzerland.

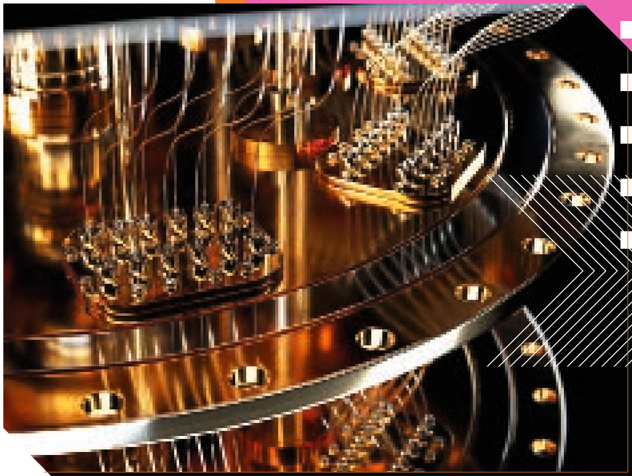
But the truth is that, as physicists have come to accept the mysterious nature of entanglement and are using it to develop new technologies, they are doubtful that it has anything left to tell us about how the universe works.

You can create quantum entanglement between particles by bringing them close together so that they interact and their properties become intertwined. Alternatively, entangled particles can be created together in a process such as photon emission or the spontaneous breakup of a single particle such as a Higgs boson.

The spooky thing is that, in the right conditions, if you then send these particles to opposite sides of the universe, performing a measurement on one will instantaneously affect the outcome of a measurement on the other, despite the fact that there can be no information exchanged between them.

For Einstein, this weirdness was an indication that something was missing from quantum theory. But these days, entanglement is just seen as a routine resource. Indeed, it no longer provokes any kind of head-scratching in the physicists who work with it on a daily basis.

"We cannot explain it in classical terms, but it's not really an issue somehow," says Mirjam Weilenmann, also at the University of Geneva. Ana Sainz, who works with entanglement at the University of Gdansk in Poland, feels similarly. "The fact that we don't see it in our macroscopic world every day makes it look weird, but I think it's just a fact of the universe," she says. ›



Entanglement is a key part of quantum computing

BARTLOMIEJ K. WROBLEWSKI/ALAMY

Actually, theorists showed in 2017 that entanglement simply has to exist for our universe to be as it is – it has nothing to do with the formulation of quantum theory itself. "Entanglement goes beyond quantum theory," says Sainz. "You can have entanglement even if quantum theory is false."

The phenomenon lies at the heart of several new kinds of technology. Even in its most basic form, "it can be super-useful for quantum computing and quantum cryptography, for example", says Artur Ekert at the University of Oxford.

Which isn't to say we understand everything about entanglement. "There are loads of open questions – some are really basic ones," says Sainz. One is simply how to measure the strength of entanglement. But although entanglement is often viewed as a mystery that holds the key to a better understanding of the universe at its most fundamental level, it might not work out like that, according to Ekert.

Entanglement has been touted as the underlying phenomenon that space-time itself emerges from, for example. And probing the phenomenon at high energies at the Large Hadron Collider at CERN, near Geneva, has recently been proposed as a route to figuring out what quantum theory tells us about the nature of reality.

But those who deal with entanglement every day are wary of such grand promises. It is already so intrinsic to our picture of the universe that there is no guarantee further experiments will reveal anything more, says Ekert. "There's much more to space and time than we understand," he says. "But is entanglement a manifestation of that? I don't know."

MB

CANCER

CANCER IS A DISEASE, or group of diseases, in which some cells proliferate uncontrollably and can spread to other parts of the body. But that description doesn't reflect how our conception of cancer has changed, says Kenneth Pienta at Johns Hopkins University in Maryland. "People used to view cancer as sort of bad luck: the cancer would just change over time and we didn't really understand why, or how, or what was driving those changes."

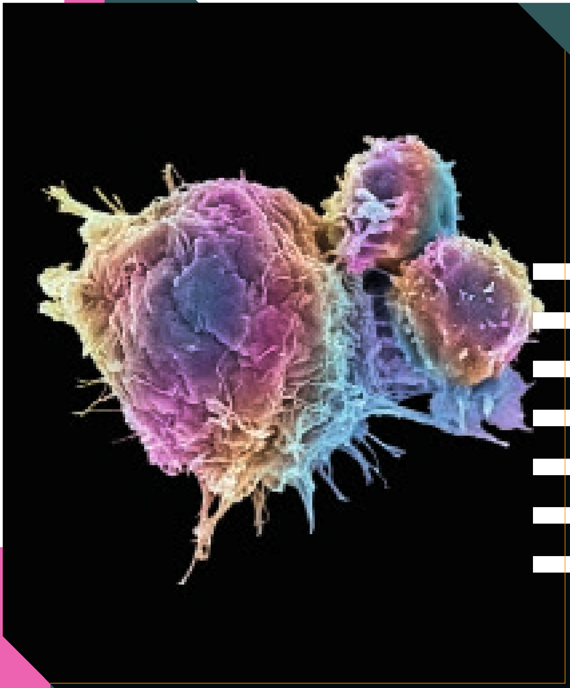
In the past few years, however, Pienta and others have come to see cancers as akin to organisms themselves, existing in complex ecosystems alongside other cancer cells and host immune cells. Cancer cells compete for access to nutrients, and only the fittest survive. "Cancer evolves in response to changes in its environment," says Pienta. "If it didn't, it would die."

Ultimately, this is the reason why cancer kills so many people. Cancer cells divide rapidly, so random mutations occur often and any that confer an advantage are quickly selected for. "They're evolving to become the best cancer cell they can become and that typically is bad news for the patient," says Robert Gatenby, co-director of the Cancer Biology and Evolution Program at the Moffitt Cancer Center in Florida.

What's more, the hardiest cells are better at getting into the bloodstream and spreading to other parts of the body, a process known as metastasis. "We have got good drugs and initial therapies for most types of cancers," says Gatenby. "But in the metastatic setting, you're almost never cured."

The good news is that viewing cancer through an evolutionary lens suggests new ways to treat it, says Gatenby. Among them is the idea that, rather than trying to wipe out cancer cells, we should manage the disease almost as if it were a chronic condition like diabetes.

Conventional treatments like chemotherapy or radiotherapy will always leave behind a small population of resistant cells. With their competition wiped out, they quickly proliferate – and the cancer becomes much harder to treat. However, Gatenby's lab is experimenting with ways to keep some treatment-responsive cells alive so that they compete with the resistant cells. "We only give a little bit of the treatment and then stop," says



A cancer cell and two immune cells

STEVE GSCHMEISSNER/SCIENCE PHOTO LIBRARY/ALAMY

Gatenby. "The tumour will come back, but because you're not applying any selection for resistance, the sensitive cells will dominate."

Another strategy could be to target cancer's ability to adapt. Pienta's team has discovered that when people are given chemotherapy, a tiny subset of cancer cells stops dividing and enters a state of hibernation. These polyaneuploid cancer cells can hide from chemo drugs. Pienta believes that by destroying them, we could collapse the whole cancer ecosystem.

It may even be possible to stop cancers before they have a chance to evolve. Charles Swanton at the Francis Crick Institute in London has found that when people experience chronic inflammation as a result of exposure to air pollution or tobacco smoke or alcohol, immune cells can kick-start cancer development. This opens yet another avenue of treatment: target the immune cells that cause cancers to grow in the first place. "The normal ecosystem is not subjected to the sort of genome instability that cancers are, so the targets are much more stable and potentially more tractable," says Swanton.

Ultimately, scientists believe that their new conception of cancer may allow us to cure it. "Our big advantage is that cancer cells can only adapt to the here and now," says Gatenby. "They can never anticipate the future. But humans can."

Jasmin Fox-Skelly

RON KOEBERER/MILLENNIUM IMAGES, UK

SCALE

IMAGINE SETTING OFF on a spacecraft that can travel at the speed of light. You won't get far. Even making it to the other side of the Milky Way would take 100,000 years. It is another 2.5 million years to Andromeda, our nearest galactic neighbour. And there are some 2 trillion galaxies beyond that.

The vastness of the cosmos defies comprehension. And yet, at the fundamental level, it is made of tiny particles. "It is a bit of a foreign country – both the small and the very big," says particle physicist Alan Barr at the University of Oxford. "I don't think you ever really understand it, you just get used to it."

Still, you need to have some grasp of scale to have any chance of appreciating how reality works.

Let's start big, with the cosmic microwave background (CMB), the radiation released 380,000 years after the big bang. "The biggest scales we've measured are features in the CMB," says astrophysicist Pedro Ferreira, also at the University of Oxford. These helped us put the diameter of the observable universe at 93 billion light years.

At the other end of the scale, the smallest entities are fundamental particles like quarks. Yet quantum physics paints these as dimensionless blips in a quantum field, with no size at all. So what is the shortest possible distance? The best we can do is the so-called Planck length, which is about 100 billion billion times smaller than a proton.

This arises out of an idea in quantum mechanics known as Heisenberg's uncertainty principle, which says that certain pairs of properties, including position and momentum, can't both be known precisely at the same time. The upshot is that we can never measure anything beneath the Planck length, no matter how advanced our technology. Similar constraints apply to measuring other things, such as energy, too.

> "THE NUB OF THE PROBLEM IS THAT REALITY APPEARS TO OPERATE DIFFERENTLY AT VARIOUS SCALES"

For physicists, though, the challenge goes way beyond just measurement. The nub of the problem is that reality appears to operate differently at various scales, making it maddeningly hard to pin down a unified description of everything.

Take the four fundamental forces of nature. The strong force binds quarks together to make subatomic particles such as protons and neutrons, the weak force corrals neutrons and protons in atomic nuclei, while the electromagnetic force keeps the whole atom together, electrons included. These three forces are way more muscular than the fourth – gravity. Even the weak force is 10^{24} times stronger than gravity. Naturally, physicists want to understand why there is such a huge discrepancy.

To make matters worse, we are also forced to use separate theories to describe these forces. Albert Einstein's theory of general relativity describes gravity on the scale of stars and galaxies. Meanwhile, the other three forces are governed by quantum mechanics, which applies to the subatomic realm. We have yet to find a way to meld the two into a theory of quantum gravity. "One of the biggest problems in physics is the disparity in scales between the size of atoms and the size of the universe," says Barr.

Perhaps our struggles with scale are telling us something deeper about the universe. Maybe, at the fundamental level, there is no scale at all.

That is the idea being pursued by Manfred Lindner at the Max Planck Institute for Nuclear Physics in Germany via a hypothesis called "scale symmetry". The basic idea is that scale is "emergent", in the sense that it arises from the collective effect of more fundamental entities for which scale is meaningless. "At the end of the day, all scales in nature are a quantum effect," says Lindner. ▮

Chen Ly