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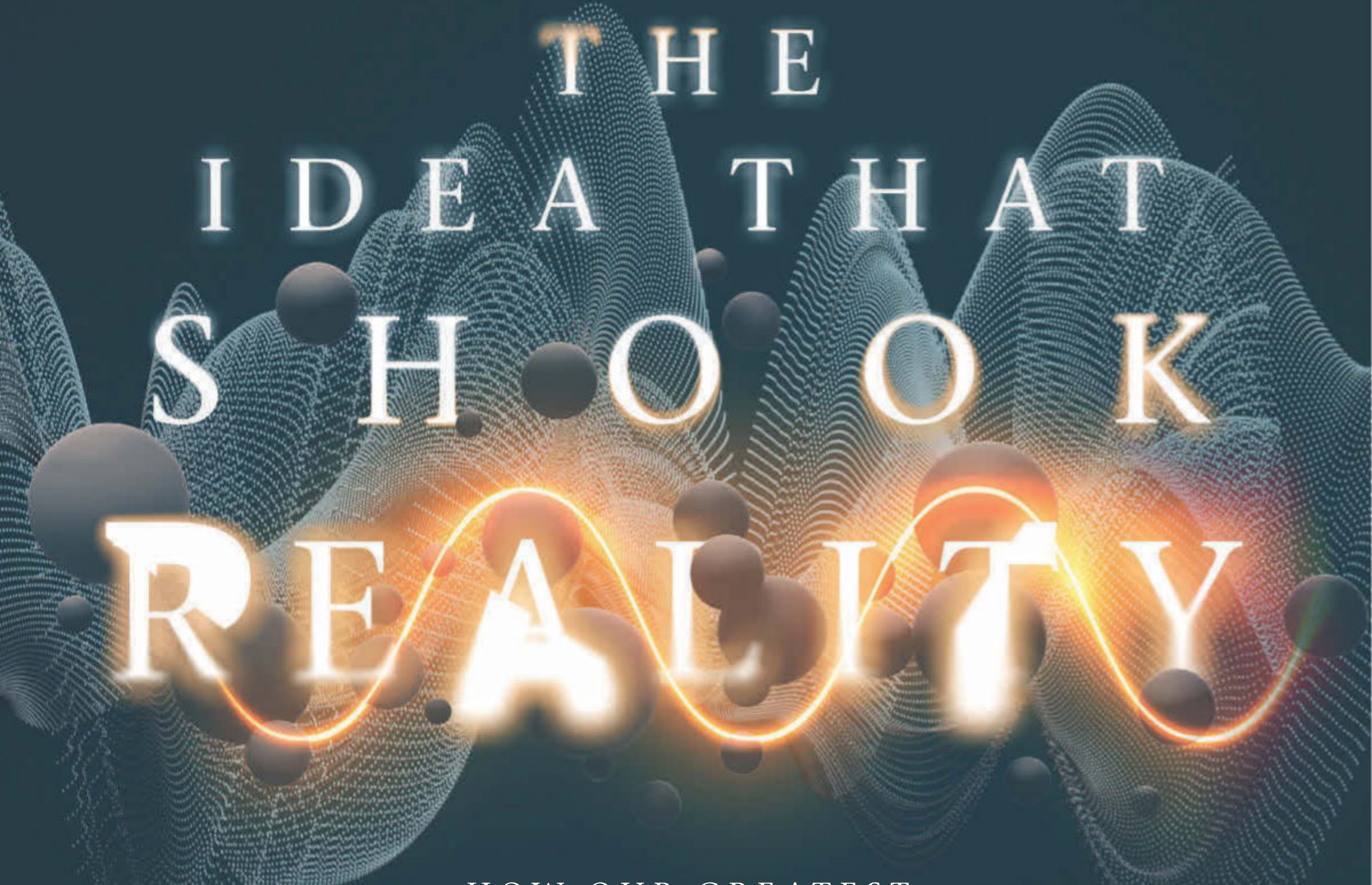

THE IDEA THAT SHOOK REALITY

HOW OUR GREATEST PHYSICS THEORY HAS TRANSFORMED OUR VIEW OF THE UNIVERSE

A SPECIAL ISSUE

PLUS GLORIOUS ANCIENT TREES / HOW LONG IS A DAY ON URANUS? / BETTER COFFEE ACCORDING TO PHYSICS / **BLACK MIRROR IS BACK**

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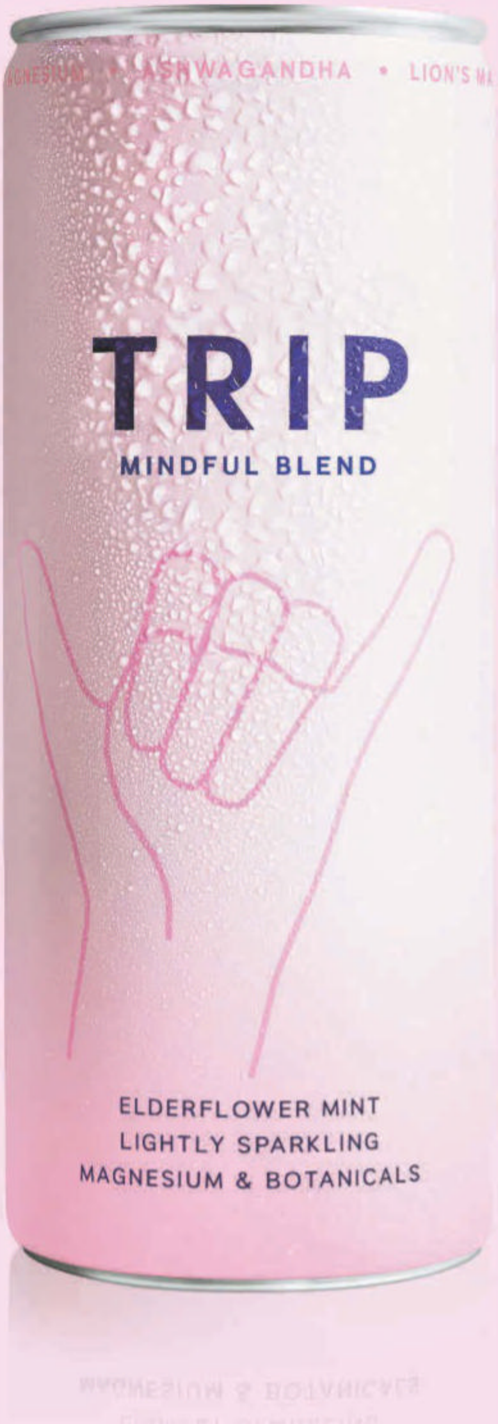
Calm is just a can away



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Elsewhere on New Scientist

Instant Expert

Consciousness and the mind-body connection

Discover the intriguing links between our physical and mental worlds, such as the strange effects of placebos and nocebos, and interoception – our ability to sense the body's internal signals. Join six world-leading experts at London's Congress Centre on 26 April to find out what this all means for our future health and the mysteries of consciousness.

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Tour

The birth of modern medicine: Paris, France

Discover the foundations of the modern science of medicine, where the "Paris School" of hygiene and hospital teaching flourished during the 18th century. From mummified écorché figures to bone-lined catacombs, you will learn about the early history of medicine with historian Richard Barnett. This five-day tours starts on 20 July and costs £2557.

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Podcast

Weekly

The team discuss the continuing existential crisis facing US science following the Trump administration's wide-ranging cuts. There is also the news that physicists have cracked how to brew the best cup of coffee. Plus, what to make of the claim that Colossal Biosciences has brought the dire wolf, an animal that went extinct thousands of years ago, back to life.

newscientist.com/nspod

DAVID STOCK

Pollution blues Mandy Barker creates images of discarded clothing

BONKERSABOUTPICTURES/ALAMY

Parisian catacombs Explore the history of hygiene and medicine

Video

Fast fashion cyanotypes

In artist Mandy Barker's new book, *Photographs of British Algae: Cyanotype imperfections*, she uses the early photographic process of making cyanotypes to highlight the ongoing pollution crisis in our oceans. Barker took discarded clothing that had washed up on beaches along the British coastline and transformed them into images that look almost botanical.

youtube.com/newscientist

Newsletter

Our Human Story

English is one of more than 400 Indo-European languages, including French, Greek, Bengali, Sanskrit and many others that are all believed to have originated from the same place. But where was this Indo-European homeland? And how did this one language family spread so widely?

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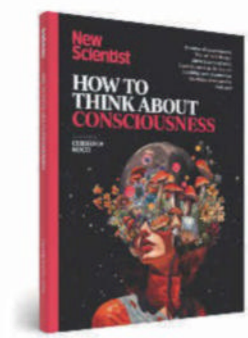
Podcast

"Under the fur, these wolf pups are nothing like the extinct dire wolf"



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Beyond weird

As quantum theory turns 100, let's celebrate its power – and provocation

YOU might say it all started with a spot of hay fever. In June 1925, a young physicist named Werner Heisenberg retreated to the barren island of Helgoland in the North Sea, seeking respite from his allergies. There, he scribbled down equations that would light an intellectual fire in Europe, eventually forming the basis of an idea that shook our view of how reality works to the core. That idea was quantum theory.

In recognition of the quantum centenary, the United Nations has designated 2025 as the International Year of Quantum Science and Technology. There will be celebrations, exhibitions and conferences all over the world.

If you know only one thing about quantum theory, it is probably that it is "weird". Indeed, the idea that the quantum world is too strange to fully understand has infected our culture. There are even products like cosmetics branded or described as "quantum", a tacit signal that they have powers beyond our comprehension.

"The idea that the quantum world is too strange to fully understand has infected our culture"

It is true that quantum theory paints a strange picture of the subatomic world – but to stop there would be to miss its true importance. In this centenary year, we should be celebrating the theory for its power and provocation – as we do in a trio of articles in this special issue.

On page 29, physicist Carlo Rovelli gives us his take on the origins of quantum mechanics and introduces its bold claims. On page 32, we see how these ideas have revolutionised technology – and how they will continue to do so. And on page 35, we explore the profound questions quantum theory forces us to ask about what "real" really means. The fact that it paints such an uneasy picture of the subatomic world hints that we are missing something about the workings of the universe – but new interpretations and experiments are inching us towards a fresh understanding.

Quantum theory has been wildly successful, too. Few other scientific ideas have passed so many experimental tests. Its origins may hinge on a bout of hay fever, but it is a legacy not to be sniffed at. ■

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Hidden treasures
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Ornithology

A layover at the lake

Every long journey needs breaking up, even those of great white pelicans (*Pelecanus onocrotalus*), pictured here resting last month at Lake Çavuşçu in Konya, Turkey, while on their migration to breeding grounds that range from eastern Europe to Kazakhstan. Their migratory routes aren't well understood, but this lake is a popular stopping point each year.

SEYIT KONYALI/ANADOLU VIA GETTY IMAGES

Neuroscience

First synapse engineered in mammals

An artificial electrical synapse has been created in mouse brains thanks to gene editing, a technique that could be used to help treat mental health conditions, finds **Chris Simms**

ELECTRICAL synapses that carry messages through the brain have been artificially engineered in mammals for the first time, altering their behaviour. This could have potential for preventing or treating a range of mental health conditions, including obsessive compulsive disorder (OCD).

Connections, or synapses, between nerve cells are either electrical or chemical. Chemical ones, which are more common in mammals, involve molecules called neurotransmitters, whereas electrical synapses rely on proteins called connexins.

"We have found a way to edit connections between cells, enabling targeted rewiring of the brain"

Many mental health conditions seem to occur when things go wrong with the neurotransmitter-based signalling system, says Kafui Dzirasa at Duke University in Durham, North Carolina. "We wanted to know if we could engineer a way to bypass the chemical synapses between cells by putting an electrical synapse there," he says.

First, Dzirasa and his colleagues looked for proteins from other organisms that could be used to build an electrical synapse in mice. Similar work was previously done in the nematode worm *Caenorhabditis elegans*, but that animal has only 302 neurons, so it was relatively simple, whereas mice have about 71 million neurons.

"We found [the connexins] by searching an incredible amount of literature to find proteins with exactly the properties that we'd want to engineer a human system with," says Dzirasa.

They opted for connexins called 34.7 and 35, found in a fish called the white perch (*Morone americana*). These connexins would later be used by the nerve cells on either side of the junction at the synapse, like the positive and negative parts of a circuit.

After identifying the right proteins, the next issue was knowing where to place them. "We implanted lots of electrodes about the size of a hair into many brain areas at the same time in mice and then we recorded their electrical activity," says Dzirasa. "This gives an electrical map of how information is flowing through the brain."

The team then exposed the mice to situations that induce behaviours like anxiety or aggression to see how this flow changed, pinpointing which brain cells should receive the engineered synapse.

Once these had been identified, the researchers injected a harmless virus into the mice's brains to deliver the genetic information needed to make the connexins. This resulted in working electrical synapses that changed how electricity moved in a microcircuit in the frontal cortex. The mice then showed signs of being more explorative and sociable, suggesting this approach could help treat conditions like social anxiety.

Brain training

"It's a cute idea," says David Spray at the Albert Einstein College of Medicine in New York. "It will likely provide a useful tool to answer the question of what would happen to activity patterns and behaviours if we added electrical synapses to specified cell types in neural circuits."

The researchers also did a further experiment investigating the potential of this technique to prevent mental health issues. "We wanted to know if we could use this tool to promote resilience," says Dzirasa.

To attempt this, he and his colleagues targeted a long-range circuit between the frontal cortex and an area of the brain called the thalamus. They identified this circuit as important when mice are stressed, which is a sensation they may respond to by freezing in place. Introducing the engineered electrical synapses enhanced communication between these regions and stopped the mice from freezing (bioRxiv, doi.org/pg4m).

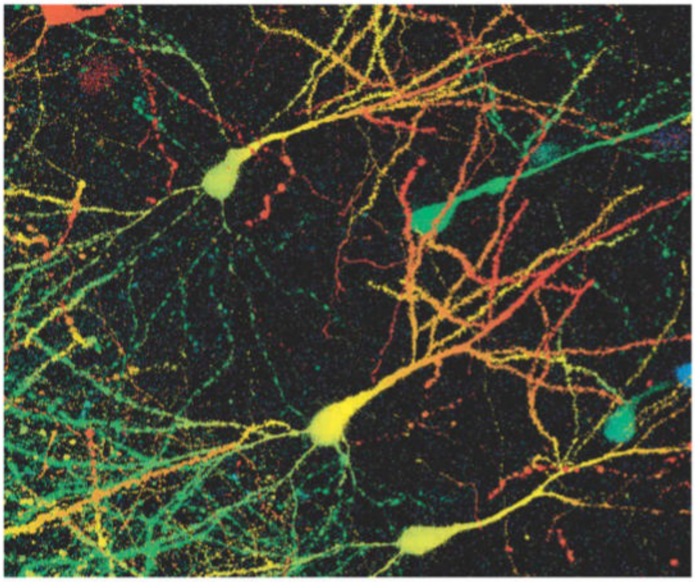
"We have created an approach to edit the connection between cells, enabling targeted rewiring of the brain," says Dzirasa. "It has the potential to edit many different types of genetically inducted wiring deficits to prevent the emergency of psychiatric disorders."

Katrin Amunts at the Jülich Research Centre in Germany says that while the research is at an early stage, the scientists "demonstrate in the mouse model that a targeted change at the subcellular level can have an effect at the behavioural level, so there is psychiatric relevance".

Further work by Dzirasa and a different group of colleagues introduced connexins into juvenile mice genetically predisposed to develop OCD-like symptoms (bioRxiv, doi.org/pg4n). "Normally, over time, the mice start grooming a lot, and the grooming can be so severe that they get these huge facial lesions that mirror the lesions that some people with OCD get when they compulsively wash their hands," says Dzirasa.

The mice with the electrical synapses groomed less and about two-thirds of them never developed facial lesions.

Despite the work being done in mice, Dzirasa selected connexins 34.7 and 35 partly on the basis that they should work similarly in people. Existing atlases of



DR GOPAL MURTI/SCIENCE PHOTO LIBRARY

Mouse neurons coloured differently according to their depth in the brain

gene expression profiles in humans could also identify which cells to target.

"These gene-expression patterns are like a GPS indicator," he says, showing which cells do what. Viruses carrying the

"Despite the work being done in mice, the proteins selected should work similarly in people"

necessary genomic material could be injected into the bloodstream and then pass through the blood-brain barrier, which could also be opened via focused ultrasound, to target cells with the right profiles, says Dzirasa.

"I'm personally very excited," says Ithai Rabinowitch at the Hebrew University of Jerusalem in Israel, part of the team that put an electrical synapse in *C. elegans*. "Engineering or editing synaptic connections provides a potential all-biological approach for elucidating neural circuit function and for potentially treating various diseases involving neural connectivity," he says. "Importantly, once installed, these new connections drive neural circuit information flow and function completely autonomously, with no need for external activation or regulation."

But brain editing in people is a long way off and raises ethical questions, says Dzirasa. "I just want to make sure there's something available for people if they need it."

Rabinowitch also wonders if the brain would respond by making new neural links that may undo the effects of the engineered synapses or create other potentially negative pathways. The intervention might also have unknown side effects, he says. ■

Briefing

No, the dire wolf isn't back

Claims that the dire wolf has been brought back from extinction are not what they seem, says **Michael Le Page**

A COMPANY called Colossal Biosciences says it has revived the dire wolf. "On October 1, 2024, for the first time in human history, Colossal successfully restored a once-eradicated species through the science of de-extinction." That's the claim made on the website of the US-based company. Here's what we know.

COLOSSAL BIOSCIENCES

Is this genetically modified grey wolf pup really the same as a dire wolf?

What's happened?

Colossal is claiming that three genetically modified grey wolf pups – two males called Remus and Romulus born in October, and a female called Khaleesi born in January – are in fact dire wolves. The same company also recently announced the creation of woolly mice and a nearly complete thylacine, or Tasmanian tiger, genome.

What is a dire wolf?

Dire wolves are large extinct canines (*Aenocyon dirus*) that lived in the Americas until around 10,000 years ago. The animals looked like large wolves with white coats. They were made famous by the *Game of Thrones* TV series – hence the name Khaleesi, after a main character in the show.

So, a dire wolf is an extinct species of wolf?

No. Grey wolves and dire wolves were thought to be very closely related based on their physical similarities, but a 2021 study of ancient DNA revealed that they last shared a common ancestor around 6 million years ago. Jackals, African wild dogs and dholes are all more closely related to grey wolves (*Canis lupus*) than dire wolves are.

20

How many gene edits Colossal made to the grey wolf genome

Does that mean there are a lot of genetic differences between grey wolves and dire wolves?

Beth Shapiro of Colossal says her team has sequenced the complete genome of the dire wolf and will soon release it to the public. Shapiro couldn't tell *New Scientist* how many differences there are but said the two species share 99.5 per cent of their DNA. Since the grey wolf genome is around 2.4 billion base pairs long, that still leaves room for millions of base-pairs of differences.

And Colossal claims it has turned grey wolves into dire wolves by making just 20 gene edits?

That is the claim. In fact, five of those 20 changes are based on mutations known to produce light coats in grey wolves, Shapiro told *New Scientist*. Only 15 are based on the dire wolf genome directly and are intended to alter the animals' size, musculature and ear shape. It will be a year or so before it is clear if those changes have had the intended effects, says Shapiro.

So these pups aren't really dire wolves at all, then?

It all comes down to how you define species, says Shapiro. "Species concepts are human classification systems, and everybody can disagree and everyone can be right," she says. "You can use the phylogenetic [evolutionary relationships] species concept to determine what you're going to call a species, which is what you are implying… We are using the morphological species concept and saying, if they look like this animal, then they are the animal."

What will happen to the gene-edited grey wolves that look a bit like dire wolves?

Shapiro says they are being raised on an 800-hectare reserve where they are being observed and cared for. There are no plans to allow them to breed. ■

Physics

Space could emerge from time

An investigation of the behaviour of a single quantum bit through time has uncovered a tantalising similarity to the geometry of three-dimensional space, finds **Karmela Padavic-Callaghan**

PHYSICISTS of the 19th century assumed space was distinct from time – and two researchers now suspect they were correct to do so. Their conclusion, which comes from considering the behaviour of quantum bits, or qubits, questions the now-dominant idea that four-dimensional space-time is the fundamental fabric of physical reality.

A qubit is an object that has two possible states – for example, two different spins. Because it is quantum, a qubit can also exist in combinations of those states that any familiar object could never take on – a phenomenon known as a superposition.

For years, physicists have found the mathematics of qubit states to be "extremely suggestive" of some deeper connection to the geometry of space, says Vlatko Vedral at the University of Oxford. Now, he and James Fullwood at Hainan University in China have made a mathematical argument for how the geometry of space may be encoded in a qubit's behaviour in time.

PETER JURIK/ALAMY

Space-time is thought to be the fabric of physical reality

Spaced out

They started with a mathematical model for a single qubit that an experimenter can subject to a sequence of measurements over the course of a given period of time. Within this model – and without assuming anything about the qubit's initial state – they analysed what the correlations between the outcomes of such measurements would be when considered across different time intervals.

The process is a little like analysing whether what the qubit is doing today is related to what it was doing over the preceding 24 hours, or to what it was doing over the preceding 48 hours, and so on.

They found that the structure of these correlations was mathematically similar to three-dimensional space. Specifically, from a qubit's behaviour through time, the researchers retrieved a formula for measuring distances in space – the so-called Euclidean metric (arXiv, doi.org/pgn3).

Vedral says the geometry of space that we live in is more complex than the version they uncovered through their calculations of the qubit's behaviour through time. But retrieving the Euclidean metric from such a minimal set-up and with no prior knowledge of the qubit could still be an indication that space is related to time and quantum information. "It's interesting that a single qubit suffices to actually get fully three-dimensional Euclidean space," he says.

But there is another tantalising implication in the work: that time is somehow separate from space, because the geometry of the latter can be derived from it. Space and time are typically considered to be components of a four-dimensional continuum we know as space-time, which underlies our physical world. Tearing them apart would violate the laws of Albert Einstein's special relativity, and as such, it is a controversial idea.

There are, though, other researchers who argue that space and time should be separated. For instance, Lee Smolin at the Perimeter Institute in Canada says that, in his view, time is more fundamental than space. However, he doesn't think of time existing in a way that can be captured with the equations in the new study.

"Space-time may well be a fiction. It's useful, but in the final analysis, you won't really need it"

His hypothesis, which is also not mainstream, is that "time is not something that is frozen or needs structure", but should be understood as a succession of present moments that occur one after another – with no physically meaningful, or knowable, past or future.

Time and again

Thomas Galley at the Institute for Quantum Optics and Quantum Information in Vienna, Austria, says it may be intuitive to think that time is somehow different from space simply because we experience it as such. But a thorough mathematical understanding of what that means in the context of qubits is still rather elusive.

For instance, Galley points out that the new study, while interesting, doesn't elucidate an exact mechanism by which space would emerge from the qubit and time. Moreover, the proposition that "qubit plus time equals space" may not be unique, as it may turn out to be possible to swap the qubit for a more complicated quantum object and still extract a Euclidean metric, says Galley.

Vedral says there may be ways to test some of these theoretical ideas through experiments in the future. Ultracold quantum objects can assume superposition states like the qubit in the new work, as can physical qubits similar to those used in quantum computers.

But it is likely that many questions will remain – which means physicists may still be debating how we should think about space-time for years to come.

"It seems to me that space-time may well be a fiction, in the sense that it's a useful, convenient way for us to talk about things that happen in the universe, but in the final analysis, you won't really need it," says Vedral. ■

For more on quantum physics, turn to our special on page 28

Should we give up on recycling plastic?

Globally, only a small percentage of the plastic we use is recycled – but new technologies could change the picture drastically, finds **Madeleine Cuff**

IN 2022, the world discarded around 268 million tonnes of plastic waste, but just 14 per cent of that – around 38 million tonnes – was recycled, according to a new analysis. The rest was either burned or, more likely, dumped in landfill.

Despite growing concern over the public health and environmental impacts of plastic pollution, the global recycling rate for this material has remained largely stagnant for years. Is it time to admit defeat for plastics recycling?

Reduce, reuse, recycle?

There is no denying this is a tricky problem to solve. Plastic use has exploded around the world in recent decades, but many countries still lack the collecting, sorting and processing facilities needed to deal with all the rubbish. Only about 27 per cent of plastic waste is even collected and sent for sorting and potentially recycling, and just half ends up actually getting recycled.

Part of the problem is that a large proportion of the waste is consumer waste, says Quanyin Tan at Tsinghua University in China, who worked on the analysis (*Nature Communications Earth & Environment*, doi.org/pgtb). "Consumer waste, particularly packaging, is a major contributor to the plastic waste problem, accounting for 44 per cent of global plastic use."

Consumer packaging is cheap and discarded quickly, often used only once before being thrown away. It is expensive for recycling companies to collect and sort, and the sheer variety of plastic types and additives used in packaging makes it tricky to distinguish between what can be recycled and what can't. Even if an item can be recycled, it is often cheaper for manufacturers to buy virgin plastic instead, weakening the case for investing in new recycling capacity.

Added to this, many countries don't have the basic infrastructure – kerbside waste collections, for instance – to manage comprehensive recycling systems. It's not just a problem for low-income nations: in the US, only 5 per cent of plastic waste is recycled, and more than three-quarters is sent to landfill.

"We have this existing large-scale infrastructure of making new plastics, and then a not-so-developed infrastructure for recycling plastics," says Agi Brandt-Talbot at Imperial College London.

Instead of recycling, increasing numbers of countries are opting to burn their rubbish, with 34 per cent of plastic waste disposed of this way in 2022. In some regions, the proportion is much higher: Japan, China and the European Union, for example, burn 70 per cent, 60 per cent and 38 per cent of their plastic waste, respectively.

In some ways, incineration is better than landfill, because it can be used to generate energy – but it releases greenhouse gases in the process. "It's not a circular use of plastic," says Brandt-Talbot.

Despite these challenges, we shouldn't rush to abandon recycling completely. Where countries do have robust systems and supportive policies in place, plastic recycling rates are much higher than the global average. In Japan, the plastic recycling rate is almost 20 per cent, while in China it is 23 per cent.

The key is to get the right mix of regulations, public behaviour and policies in place, says Andrew Dove at the University of Birmingham, UK. "It is a global problem. But each country has its own waste-management systems, its own policies around plastic management and waste," he says. "It's a global problem with local solutions."

268

How many million tonnes of plastic was discarded globally in 2022

14%

Proportion of the world's plastic waste that was recycled in 2022

5%

How much plastic waste in the US is recycled

JUNI KRISWANTO/AFP VIA GETTY IMAGES

The amount and variety of plastic we use can make it difficult to sort

Back to basics

Yet even with perfect collection and sorting systems, there is a limit to what can currently be achieved. So many different types of plastics are being churned out every day, and only a small fraction can be recycled, Dove points out. "We've been developing plastics quite happily for 70-odd years, optimising them, making them better and more complicated to do more things," he says. "And what we have not been doing at the same rate is developing the end-of-life treatments."

The good news is that progress is being made, says Dove. New technologies are unlocking routes to chemical recycling, for example, where plastics are broken down into their original chemical building blocks. "The public, policy-makers and scientists now care enough about this that new technologies are going to be developed, scaled and implemented," he says. "You are seeing a lot more technologies come through that are focused on the sorting problems, on simplifying what we are making to get the same performance from more simple plastics, and then on recycling complicated and mixed materials."

These innovations should start to push the global recycling rate higher, he argues. Meanwhile, if you are in a country with a good recycling system, keep putting those bottles out for collection. ■

Human evolution

Denisovan discovery in Taiwan

Fossil extends the known range of these ancient humans by thousands of kilometres

James Woodford

A FOSSIL found by fishers in Taiwan has been identified as a jawbone from the mysterious Denisovan group of ancient humans.

Denisovans were first described in 2010 from a fossil fingerbone discovered in Denisova cave in the Altai mountains, Russia. Although few fossils have been found, traces of their DNA still exist in some modern humans, indicating they were widespread in East Asia.

The newly identified fossil mandible was recovered from the Penghu Channel by commercial fishers while dredging the seabed. It ended up in an antique store in Tainan City, where a local resident purchased it and donated it to the National Museum of Natural Science, Taiwan.

During previous glacial periods, when sea levels were much lower, the channel was a land bridge between the mainland and Taiwan, inhabited not just by ancient humans, but also a suite of wildlife, whose fossils have also been recovered by fishers.

Frido Welker at the University of Copenhagen, Denmark, and his colleagues dated the mandible based on the presence of other animal species found in the channel. They identified two possible windows, suggesting the fossil is either between 10,000 and 70,000 years old, or 130,000 and 190,000 years old. "Which of the two windows is most likely cannot be said with certainty," says Welker.

To identify what kind of ancient hominin the bone came from, the team studied the proteins locked inside the fossil. Altogether, the researchers found 4241 amino acid residues from 51 proteins, including two protein variants that were specific to Denisovans.

By comparing the protein sequences with other ancient humans, the researchers confirmed that the mandible belonged to a Denisovan and not a Neanderthal or a modern human (*Science*, DOI: 10.1126/science.ads3888).

From the enamel on a tooth, the team also recovered a variant of a protein that is coded on the Y chromosome, showing that the fossil belonged to a male.

Fossils identified molecularly as Denisovans have previously been found only in Siberia and on the Tibetan plateau. "The Taiwan Strait is thousands of kilometres away. There are many fossil locations between those three sites, and so some of those fossils could be Denisovans, too," says Welker.

Takumi Tsutaya, a team member at the Graduate University for Advanced Studies in Kanagawa, Japan, says the study suggests that a number of mysterious Chinese fossils from the Middle to Late Pleistocene are actually Denisovans.

"This is because the fossils that have been genetically confirmed to be Denisovans are mostly lacking in morphological information, and the fossils with distinct morphological features have not been examined genetically," says Tsutaya. "In the future, if the latter fossil group is examined through the analysis of ancient proteins or ancient DNA, the evolutionary positioning of the Denisovans will become clearer."

This mandible fossil was found by fishers while dredging the seabed

YOUSUKE KAIFU

Reproductive health

World's first baby born by IVF done mostly by a machine

A HIGHLY automated form of in vitro fertilisation (IVF) has led to a successful birth, raising hopes that this approach could cut the risk of human error during such procedures.

One method of IVF is intracytoplasmic sperm injection (ICSI), where sperm is injected into eggs in a lab dish. This is commonly used in cases of male infertility, as the sperm don't have to work to reach an egg. It relies on high levels of precision and errors can reduce the odds of fertilisation.

To address this, Jacques Cohen and his colleagues at Conceivable Life Sciences, a biotech company in New York City, have developed a machine that can perform 23 key steps required for ICSI (*Reproductive BioMedicine Online*, doi.org/g9d3vq). Each one is initiated by a person through the press of a button as they watch a livestream.

In one step, the machine uses an AI model to select the healthiest sperm cells for fertilisation, based on their appearance. It later injects the sperm into already-collected eggs. A similar approach has been tested before, resulting in two live births, but some steps weren't done by a machine.

The researchers recruited a couple who were struggling to conceive, partly because the man had sperm that couldn't swim properly. The woman also had problems producing eggs, so donor ones were used.

The researchers randomly assigned five out of eight donor eggs to be fertilised by the machine, which produced four embryos. The three remaining eggs were fertilised using the manual ICSI approach, all of which formed embryos.

"In one step, the machine uses an AI model to select the healthiest sperm cells for fertilisation"

An AI model selected the two most promising embryos, based on their chromosomes' appearance. Both were produced using the automated system, but that doesn't necessarily mean it produces healthier embryos than manual ICSI, says Cohen.

When the team inserted one of the embryos into the woman's uterus, it failed to develop, but the second led to a successful birth.

Carissa Wong

Climate change

Methane-eating bacteria ready to tackle emissions

Madeleine Cuff

METHANE leaks from sites like rice paddies, landfills, dairy farms and coal mines could be plugged with the help of gas-guzzling bacteria, helping to curb near-term global warming.

Later this year, researchers in the US will deploy a bioreactor filled with a specially bred strain of methane-eating bacteria at a landfill site in Washington.

They hope the field test will prove that these bacteria, known as methanotrophs, can be deployed in bioreactors such as this to harvest methane from the air, even when it is at relatively low concentrations.

"Since existing bacteria are designed by nature to carry out this work, the vision is to harness this natural capability in a modular, scalable technology that can be deployed anywhere in the world," says Mary Lidstrom at the University of Washington.

Methane has a relatively short lifespan in the atmosphere, lingering for around seven to 12 years, but it traps much more heat than carbon dioxide. Cutting methane emissions is therefore a key route to slowing near-term warming of the climate, yet despite this, methane emissions have been rising in recent years.

The largest sources of methane emissions are agriculture, fossil fuels and landfill waste, all of which the bioreactors will target. They are giant tanks, similar in size to a shipping container, housing specially bred strains of *Methylomicrobium buryatense 5GB1C*, a methanotroph first found in a lake in Russia.

Lidstrom and her colleagues have been working to improve this microbe's ability to harvest methane even at relatively low concentrations of around 100 to 1000 parts per million, similar to the levels found near methane leakage sites like landfills.

The methane-laden air will flow through the bioreactor, allowing the methanogens inside to consume the gas. The methane will be converted into proteins, which will be harvested and sold for animal feed, and carbon dioxide. While this means small amounts of greenhouse gas will still be released, the net effect is a reduction in the warming capacity of the air. The team expects the bioreactor to cut methane concentrations by 60 to 80 per cent in air that has been treated.

"This is a technological solution that can work," says Jessica Swanson at the University of Utah, who is also working on the project. A second pilot at the landfill is also being planned for this year, alongside another at an agricultural site, probably a dairy or pig farm.

> "We're very fortunate that microbes have evolved this capacity to bind methane"

Once they are scaled up, these bioreactors could be removing 24 million tonnes of CO_2-equivalent by mid-century.

Lisa Stein at the University of Alberta in Canada is working on a similar concept that will use methanotrophs encased in hydrogels to extract methane from wetlands. She says methanotrophs have "huge potential" to tackle real-world emissions. "We're very fortunate that microbes have evolved this enzymatic capacity to bind methane and oxidise it to carbon dioxide and also assimilate it into biomass," she says. ■

Zoology

Dolphins still harmed by banned chemicals

Melissa Hobson

WAVES & WELLIES PHOTOGRAPHY

DOLPHINS in seas around the UK are dying from a combination of increased water temperatures and toxic chemicals that the UK banned in the 1980s.

Polychlorinated biphenyls (PCBs) are a long-lasting type of persistent chemical pollutant, once widely used in industrial manufacturing. They interfere with animals' reproduction and immune response and cause cancer in humans.

In a new study, researchers showed that higher levels of PCBs in the body and increased sea surface temperatures are linked to a greater mortality risk from infectious diseases for short-beaked common dolphins (*Delphinus delphis*), a first for marine mammals.

The ocean is facing "a triple planetary crisis" – climate change, pollution and biodiversity loss – but we often look at threats in isolation, says Rosie Williams at Zoological Society of London.

Williams and her colleagues analysed post-mortem data from 836 common dolphins stranded in the UK between 1990 and 2020 to assess the impact of these threats.

They found a rise of 1 milligram of PCBs per kilogram of blubber was linked with a 1.6 per cent increase in the chance of infectious diseases, such as gastritis and pneumonia, becoming fatal. Every 1°C rise in sea surface temperature corresponded to a 14 per cent increase in mortality risk.

Sea temperatures and toxic chemicals increase mortality risk for common dolphins

The study found the threshold where PCB blubber concentrations have a significant effect on a dolphin's risk of disease is 22 mg/kg, but the average concentration in samples was higher, at 32.15 mg/kg (*Communications Biology*, doi.org/pgtj).

Despite being banned in the UK in 1981 and internationally in 2001, PCBs are still washing into the ocean. "They are still probably entering the environment through stockpiles and are often a side product or a byproduct of other manufacturing processes," says Williams. Cleaning up PCBs is very difficult. "Because they're so persistent, they're a nightmare to get rid of," she says.

These findings indicate what might happen if action isn't taken to ban perfluoroalkyl and polyfluoroalkyl substances (PFAS), another widespread group of so-called forever chemicals. ■

Environment

Trees capture toxic fingerprint of gold mining

James Dinneen

MERCURY pollution accumulated in trees offers a new way to keep tabs on destructive gold mining operations in the Amazon.

"We could potentially see whether mining is starting to ramp up," says Jacqueline Gerson at Cornell University in New York.

Most small-scale gold mining operations separate gold from ore by adding liquid mercury and then burning the mixture, releasing large amounts of mercury – a potent neurotoxin – into the air. Together, these mining operations, many of which are illegal, represent the largest source of mercury pollution in the global environment.

While stripped forest and flooded land can be a telltale sign of mining, the mercury released by these operations is more difficult to track. It is "completely invisible", says Gerson. However, trees growing near mining sites are known to take up the pollution.

To test whether the trees might offer a reliable way of measuring mercury, Gerson and her colleagues working in the Peruvian Amazon took cores from the trunks of wild fig trees (*Ficus insipida*), one of the few tropical tree species that produces seasonal growth rings. Three of the sites from which they took cores were within a few kilometres of known mining activity, while two were far from any known mining.

They found mercury levels were highest in the tree cores collected from sites near mining activity, especially those from the two sites near mining towns where most mercury burning happens. The pattern of mercury concentration in the trees also closely tracked independent measures of mercury in the air at each of the sites (*Frontiers in Environmental Science*, doi.org/pgj2). "The tree is just reflecting what the atmosphere is doing," says Gerson.

This suggests the trees could be used to track mercury emissions, even in remote parts of the forest that lack the right equipment.

Today, record-high prices for gold threaten to expand mining operations, says team member Luis Fernandez at Wake Forest University in North Carolina. Yet US federal funding for effective interventions is being slashed, including for Fernandez's own research consortium on mercury pollution. ■

A gold mining area in the southeast of the Peruvian Amazon

ERNESTO BENAVIDES/AFP VIA GETTY IMAGES

Technology

AI-powered chilli spray could safely deter bears

Matthew Sparkes

AI-CONTROLLED machines equipped with chilli pepper spray could reduce confrontations between bears and people. But the animals may learn to avoid these machines and simply head to homes and rubbish dumps without them.

FLPA/ALAMY

There have been clashes between people and Tibetan brown bears

Incidents between people and Tibetan brown bears (*Ursus arctos pruinosus*), also known as Tibetan blue bears, on the Tibetan Plateau are escalating. This may be at least partly due to climate change affecting the animals' usual territory. That could result in bears killing livestock and damaging property, or even severe injuries or fatalities for bears or humans.

In an effort to solve the problem, Pengyu Chen at Wuhan University in China and his colleagues have created a machine that uses AI to identify bears and spray them with an unpleasant, but safe, concoction of 5 per cent capsaicin, the chemical that gives chilli peppers their heat, and up to 2 per cent menthol.

The researchers trained their AI model on more than 1000 images of local wildlife, of which over 600 were photographs featuring bears. Yaks, antelopes and even people were also featured, but the model was trained to target only bears.

The researchers then designed a device that included the spray, a camera, a small computer to run the AI model, a 1-watt solar panel and a 11,000-milliamp-hour lithium battery, which could run without charging or maintenance for up to 30 days. When activated by the computer, the spray could hit bears at distances of up to 13 metres.

In tests, the researchers found that 91.4 per cent of the time that the machine – which costs just over £50 to make – identified a bear, there was actually a bear; meanwhile, 93.6 per cent of the time that there was a bear present, the machine identified it (arXiv, doi.org/pgjx).

There was also a 1.8 per cent chance of a person being accidentally sprayed when walking within range of the device. The researchers didn't respond to a request for comment, but in their research wrote that adding infrared sensors or acoustic sensors could improve the model's accuracy.

Dave Garshelis, who runs a group focused on bears at the International Union for Conservation of Nature and Natural Resources, says that the idea is sound but could have a limited effect in the long term. "Bears are very smart, and I'm sure that a bear sprayed once will never come near one of these devices again," he says. But they will probably still visit the general area and just avoid the machine itself, says Garshelis.

He says that the project reminds him of US park rangers shooting bears with rubber bullets to keep them away from people, which worked up to a point. "The bears learned to stay away from people in uniforms carrying guns, but recognised that there was no danger of other people," says Garshelis. ■

Palaeontology

Rethinking dinosaurs' decline

A drop in the fossil count doesn't mean that dinosaurs were doomed before killer asteroid hit

Sofia Quaglia

DINOSAURS probably weren't declining before an asteroid wiped them out; instead, there may just be limited fossils from that time period.

It has been hotly debated whether dinosaur populations were thriving or dwindling when a huge asteroid slammed into the planet about 66 million years ago. Specifically, a drop in the availability of dinosaur fossils leading up to the asteroid has led some scientists to believe the giants were doomed regardless.

Christopher Dean at University College London and his team analysed a dataset of more than 8000 fossils from four types of dinosaurs that lived between 84 million and 66 million years ago in North America, including *Tyrannosaurus rex* and *Triceratops*. They found many fossils of dinosaurs from 84 million to 75 million years ago – and then that number drops in the following 9 million years leading up to the Chicxulub impact. But there was more.

When calculating how much land from the years leading up to the asteroid's impact is currently accessible to palaeontologists and how many excavation expeditions have been undertaken in those areas, Dean's team found there simply aren't many of the right rocks available for today's scientists to study.

Because palaeontologists look for fossils in ancient layers of Earth's crust that have since been exposed to the surface, it is like working on "a puzzle where half the pieces are missing", says Dean.

When the researchers used ecological models to estimate the plausible number of dinosaurs in those areas – including information about the geology and geography at the time – their calculations suggested that overall dinosaur numbers stayed stable before the asteroid impact (*Current Biology*, doi.org/pgkm). There weren't fewer dinosaurs at the time; we are just less likely to find them, says Dean.

This adds to the growing body of research suggesting there is a bias in how many fossils palaeontologists can access from North America in the 9 million years leading up to the asteroid hit, according to Manabu Sakamoto at the University of Reading in the UK, who was not involved in the study. Yet, he says, this doesn't change the bigger picture of dinosaurs being in decline before the asteroid hit.

Even if dinosaurs were still populous and dominant towards the end of the Cretaceous Period, there doesn't seem to be a lot of variation in their species. Sakamoto's research suggests that, during the 175 million years dinosaurs roamed Earth, the rate at which new species of dinosaurs appeared was slowing down overall, leading to more dinosaur species going extinct than new ones evolving.

This long-term decline in dinosaur diversity still holds true, says Sakamoto, despite the new research suggesting a bias in the available fossils: "Those two things are not mutually exclusive of each other." ▮

The remains of the *Triceratops* Big John that died 66 million years ago

DOUGLAS R. CLIFFORD/TAMPA BAY TIMES VIA ZUMA PRESS WIRE/ALAMY

Physics

How to make a great cup of coffee with fewer beans

PHYSICISTS have found a way to produce the perfect cup of coffee with up to 10 per cent fewer beans.

With climate change making coffee production increasingly tricky, it is becoming more important to brew in the most efficient way possible, says Arnold Mathijssen at the University of Pennsylvania.

Mathijssen and his colleagues focused on pour-over coffee, where hot water is slowly added to grounds in a cone-shaped paper filter. Their advice can be boiled down to some very simple tips. Firstly, pour slowly: the more time the beans are immersed in water inside the cone, the more extraction takes place.

But this only works up to a point. Pour too slowly and the grounds aren't mixed up enough; they settle to the bottom and actually begin to reduce the amount of extraction. To combat this, the second tip is to pour from a height. "If you lift up the height of your kettle, you can basically just get more energy from gravity," says Mathijssen.

The team's experiments showed that coffee strength increased when pouring from 50 centimetres above the cone. But Mathijssen warns that if you pour from too high up, the stream of water begins to break up and form unconnected glugs, which again will disrupt circulation in the coffee cone. Not to mention that pouring boiling water from too high presents a scalding risk.

"Be reasonable," says Mathijssen. "First, try to be slow. Then lift [the kettle] up and go as slow as you can, but don't let [the flow of water] break up."

"As climate change makes coffee production tricky, it is more important to brew coffee efficiently"

The process is very dependent on the type of coffee, the size of the grounds, the type of kettle used and numerous other factors, but the researchers found that their technique can lead to savings of between 5 and 10 per cent in the amount of coffee needed (*Physics of Fluids*, doi.org/pgjm). Their experiments showed that the resulting brew has the same amount of dissolved solids, so it should be just as strong and flavoursome. ▮

MS

Geology

Our deepest effect on the planet

The draining of the Aral Sea for agriculture has caused Earth's upper mantle to rise

James Dinneen

UNSUSTAINABLE irrigation and drought have emptied nearly all of the Aral Sea's water since the 1960s, causing changes extending all the way down to Earth's upper mantle, the layer beneath the planet's crust. This is probably the deepest recorded example of human activity changing the solid inner Earth.

"To do something that would affect the [upper mantle] is like, whoa," says Sylvain Barbot at the University of Southern California. "It's showing you how potent we are at changing the environment."

The Aral Sea in Central Asia was once one of the world's largest bodies of water, covering almost 70,000 square kilometres. But Soviet irrigation programmes starting in the 1960s, as well as later droughts, emptied the sea. By 2018, it had shrunk by almost 90 per cent and lost around 1000 cubic kilometres of water.

Wang Teng at Peking University in China became curious about the Aral Sea after reading a book about the consequences of this environmental disaster on Earth's surface. "I realised that such a huge mass change would stimulate the response of the deep Earth," he says.

He and his colleagues, including Barbot, used satellite measurements to track subtle changes in the emptied sea's elevation between 2016 and 2020. Although much of the sea's water disappeared decades ago, they found the uplift is ongoing, with the surface rising by around 7 millimetres per year on average.

A ship graveyard near the former port of Moynaq on the Aral Sea in Uzbekistan

THEODORE KAYE/ALAMY

They then used a model of the crust and mantle beneath the Aral Sea to identify the changes deep below that could cause the observed uplift. "We find that the observations are completely compatible with a deep response to this change," says Barbot.

As the weight of water was removed, the shallower crust responded first, according to their model, by unbending. This prompted a response at depths as far as 190 kilometres below the surface, as viscous rocks in the upper mantle crept in to fill the void (*Nature Geoscience*, doi.org/pgjc). "The unbending creates space, and the rocks want to flow into it," says Barbot. This delayed response in a hot, weak region of the mantle called the asthenosphere is why the uplift is ongoing, even decades after the water was removed, he says.

Rebound in the upper mantle is known to occur after other large changes in mass at the surface, such as the advance and retreat of glaciers, says Roland Bürgmann at the University of California, Berkeley. But the response to the draining of the Aral Sea may well be the deepest example of a human-caused change in the solid Earth, he says.

In addition to illustrating the sheer scale of human activity, the uplift beneath the Aral Sea offers an unusual opportunity to estimate small differences in the viscosity of the mantle, particularly where it lies beneath the interior of a continent, says Bürgmann. "Knowing how that layer right under continents behaves is really important for people who try to understand plate tectonics." ∎

Archaeology

Settlement found from the golden age of ancient Egypt

ARCHAEOLOGISTS have uncovered an ancient Egyptian settlement beneath Hellenistic ruins in the north-western Nile delta that may be as many as 3500 years old. The find provides new evidence of Egyptian expansion during the New Kingdom, a thriving period that lasted from 1550 to 1069 BC.

"These periods are well known for being very rich," says Sylvain Dhennin at the University of Lyon, France, a member of the team that made the discovery. Some of the most powerful pharaohs, including Akhenaten, Tutankhamun and Ramesses II, lived at this time.

The site, called Kom el-Nugus, is located on a rock ridge sandwiched between the Mediterranean Sea and Lake Mariout, close to the modern city of Alexandria. Until now, it was known as a Hellenistic settlement occupied by Greeks from 332 to 31 BC sometime after Alexander the Great conquered Egypt.

"This discovery completely revises the history of Egypt's western frontier in the New Kingdom," says Dhennin.

Excavations revealed a temple, various artefacts and several mud-brick buildings. The team even found a grape crusher, suggesting the area might have been involved in wine production (*Antiquity*, doi.org/pgj5).

An amphora unearthed at the site bears the name of Meritaten, the daughter of Akhenaten and Nefertiti, which suggests the site was founded as early as the 18th dynasty, between 1550 and 1292 BC.

"Excavations revealed a temple, various artefacts and several mud-brick buildings"

The most exciting discovery, says Dhennin, is a series of blocks etched with hieroglyphics that were part of a temple dedicated to Ramesses II, who reigned from 1279 to 1213 BC.

He was instrumental in fighting off invasions from Libya, which may have been why some of the western settlements were established. ∎

Taylor Mitchell Brown

Solar system

A day on Uranus is longer than we thought

James Woodford

A DAY on Uranus just got slightly longer, thanks to more accurate measurements of its rotation period.

Figuring out the rotation period of the solar system's giant planets is hard, as ferocious wind storms make direct measurements impossible.

The first measurement of Uranus's rotation came from the Voyager 2 probe, which made its closest approach on 24 January 1986. Researchers at the time determined that the planet's magnetic field was offset by 59 degrees from celestial north, while its rotation axis was 98 degrees offset.

These extreme offsets mean that Uranus effectively rotates "lying down" compared with Earth, while its magnetic poles trace a large circle as the planet rotates. By measuring both the planet's magnetic field and radio emissions from auroras at its magnetic poles, researchers at the time found that Uranus completed a full rotation every 17 hours, 14 minutes, 24 seconds, with a margin of error of plus or minus 36 seconds.

Now, Laurent Lamy at the Paris Observatory in France and his colleagues have measured it to be 28 seconds longer. Their measurement is 1000 times more accurate, reducing the margin of error to a fraction of a second (*Nature Astronomy*, doi.org/g9dnrd).

The researchers looked at images of Uranus's ultraviolet auroras, taken between 2011 and 2022 by the Hubble Space Telescope, to track the long-term evolution of the planet's magnetic poles as they circle the axis of rotation.

The margin of error of the older measurement made it impossible to accurately determine a position on Uranus more than a few years later, but the new measurement should remain valid for decades. That means it could be relied on to calculate mission-critical objectives such as where a probe might orbit and enter the planet's atmosphere.

Health

Blood test suggests preeclampsia risk

Joanna Thompson

SOLSTOCK/GETTY IMAGES

Preeclampsia can be hard to detect in early pregnancy

PREECLAMPSIA can lead to many pregnancy complications including death, but it can be hard to detect early in gestation. A new blood test could help doctors identify those at risk of developing the condition months before symptoms start.

"We can narrow it down to about 1 in 4 pregnancies that are truly at high risk, and that's a big step," says Maneesh Jain at Mirvie, a California-based health start-up.

Preeclampsia is a type of hypertensive disorder of pregnancy (HDP) that occurs when something – scientists aren't sure precisely what – goes awry during the placenta's development. This leads to high blood pressure, which can cause cardiovascular disease, organ damage, seizures and even death. It can also harm the developing fetus.

Spotting preeclampsia and other HDPs can be difficult, however, because symptoms usually don't show up until at least 20 weeks into pregnancy. Sometimes, the signs go undetected until labour. And monitoring placental development is tough because taking a tissue sample from the organ is extremely invasive.

The blood test is relatively non-invasive, and uses RNA markers to predict whether someone is likely to develop an HDP. The test focuses on certain genes, including *PAPPA2* and *CD163*, the overexpression of which has been linked to HDPs. The researchers wanted to see whether they could detect this overexpression in blood samples.

> **"Once someone knows they are at high risk of preeclampsia, they can take action to prevent it"**

Their validation study of more than 9000 pregnant people suggests they can: Jain says the test was able to determine with over 99 per cent accuracy whether or not someone without pre-existing risk factors overexpressed the genes and was therefore at high risk of preeclampsia or another HDP. Roughly one-quarter of the participants without pre-existing HDP risk factors overexpressed the genes (*Nature Communications*, doi.org/pgh7).

People in certain demographics – for example, those with pre-existing high blood pressure or a family history of preeclampsia – are known to have a moderately higher risk of developing the condition, says Morten Rasmussen at Mirvie. But for many, it comes out of the blue.

Once someone knows they are at high risk of preeclampsia, they can take action to prevent it. Common interventions include taking drugs like aspirin, switching to a Mediterranean diet and monitoring blood pressure daily.

However, the new test only looked at people who were between 17.5 weeks and 22 weeks into pregnancy. "Ideally, aspirin has to be started prior to 16 weeks," says Kathryn Gray at the University of Washington in Seattle. "So we've missed that window already by the time most people would be getting the results of this test."

Mirvie plans to make the test commercially available soon. Once it is on the market, the team hopes others will use it to develop drugs targeted to the expression of genes like *PAPPA2*. Such molecular pinpointing "gives a much better chance for the treatment to show effect", says Rasmussen.

Gray would also like to see researchers use Mirvie's bank of RNA data to further nail down the genes behind preeclampsia risk for specific people. Narrowing the search profile could help lower the cost of the test, making it affordable for more people, she says.

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Comment

The future's bright

The idea that the rise of tech means today's young people are less intelligent than previous generations is rife – but wrong, says **Dean Burnett**

GEORGE ORWELL once wrote that every generation "imagines itself to be more intelligent than the one that went before it, and wiser than the one that comes after it".

Today, the second part of that observation feels more astute than ever, as we face constant concerns about the ways modern technology is supposedly destroying the minds and cognitive abilities of children and young people.

For decades, scientists have noted the occurrence of the Flynn effect, which essentially describes how, in terms of performance on various tests, each generation is more intelligent than the previous one. In recent years, this effect has seemingly diminished, leading some to interpret this as evidence of the damage that today's tech, via smartphones and screen time, is doing to young people.

ELAINE KNOX

But we shouldn't despair just yet, because there are other explanations for what we are seeing – and a lot of them are actually rather encouraging.

The Flynn effect is diminishing because there is no longer a substantial difference in intelligence scores between young people and those from older generations. Many would interpret this as meaning young people are becoming less intelligent. However, it could just as easily mean older people are retaining more of their cognitive abilities as they age. If anything, this is more likely to be correct. Outside of conditions like Alzheimer's, we have typically seen cognitive abilities reduce as people get older, simply due to age. But recent evidence reveals this is no longer the case for many.

This is presumably a downstream result of the greater access to early-life education, healthcare and information that those born in the 20th century increasingly enjoyed, allowing recent generations to not only become smarter, but stay that way.

Basically, the diminishing intelligence gap between older and younger people is more likely to be a sign of things getting better, rather than worse.

There are still concerns about the impact of technology on young people's intelligence and cognition. But even here, there is less cause for alarm than many headlines would have you assume.

True, there is evidence that excessive screen time can be detrimental to attention spans (and also evidence that argues otherwise), but this can be seen as more the result of unhelpful habits that can be undone by adjusting behaviour, rather than lasting disruptions to key neurological systems.

It also helps to consider how we are assessing intelligence or cognitive abilities in this context. Standardised tests that have been used for decades are all well and good, but how to precisely measure or even define intelligence has long been a controversial issue.

It could be that applying long-established frameworks of intellectual performance to young people who developed intellectually in a radically different environment to that of their parents does them a serious disservice.

For example, constantly flicking through multiple videos may strike older people as a sign of a lack of focus and attention, but being able to manage multiple information streams at once requires some considerable brain power. Video games have also been shown to improve multitasking abilities. Used properly, smartphones can actually enhance learning and education. And so on.

The idea that young people are intellectually inferior is bleakly common, but the evidence doesn't back it up. It is more that the world around us is constantly becoming more complex, and both younger and older people are adapting to deal with this admirably, albeit in different ways. ■

Dean Burnett is a neuroscientist and author of *Why Your Parents Are Hung-Up On Your Phone and What to Do About It*

Field notes from space-time

Conflict resolution

General relativity is an astonishingly beautiful theory, and grappling with why it disagrees with quantum mechanics is a joy, says **Chanda Prescod-Weinstein**

Chanda Prescod-Weinstein is an associate professor of physics and astronomy, and a core faculty member in women's studies at the University of New Hampshire. Her most recent book is *The Disordered Cosmos: A journey into dark matter, spacetime, and dreams deferred*

Chanda's week

What I'm reading

I have quite enjoyed Victoria Adukwei Bulley's gorgeous poetry collection Quiet*.*

What I'm watching

Medical drama The Pitt *is very good – and very sad.*

What I'm working on

I have two students finishing their PhDs this month!

I RARELY write much about it in my research papers, but every piece of science I have ever done either assumes the correctness of general relativity – our most fundamental theory for explaining gravity – or assumes it is a fantastic approximation of a more correct theory. When I and others in my field write up our research, we rarely say it out loud. But general relativity lurks everywhere in physics – from the way it allows us to navigate with the global positioning system to how it helps us launch and use telescopes for studying planets outside our solar system.

General relativity successfully, and quite beautifully, theorises why gravity is and what gravity does. There is no part of the visible universe untouched by this force – not even light, even though it has no mass and we wouldn't expect it to experience gravity.

Isaac Newton's 1687 law of gravity, and his notions of absolute space and time, turned out to be incorrect. General relativity, established by Albert Einstein in 1915, invites us to rethink the fundamental nature of reality, and it also gets used in nearly every single area of physics and every area of astronomy. Many university classes in these fields tend to start by teaching Einstein's special relativity, which theorises that space and time cannot be separated and must instead be thought of as a unified entity, space-time.

Practically speaking, this means we measure distances and times differently. The ruler used to make measurements in Newtonian physics doesn't work when we take the universal speed limit – the finite speed of light – into account. This is the stage at which students are introduced to the mathematical concept we use to measure distances, the metric. The metric, which abstracts the everyday notion of a ruler, was lurking in our Newtonian calculations, but we never had to discuss it. Special relativity is the first time we have to acknowledge it.

General relativity, colloquially known to physicists as GR, builds on the unification of space-time by taking gravity into account. Its most memorable lesson is that space-time curves: the metric that we met in special relativity must allow for the possibility that our ruler bends and isn't straight. That curvature manifests as a force, gravity. Where there is more bending, we see stronger gravitational effects. In other words, as I wrote in my first book, space-time isn't straight.

> **"General relativity is like a puzzle where the pieces fit perfectly and if we change even one it stops working"**

When I was a student, I was very focused on understanding the calculational tools involved. We had to abstract space and time for the first time, to understand the general mathematical idea of a "space". When I learned enough to put the pieces together, I was astonished by the beauty of the theory. General relativity is like a puzzle where the pieces fit together perfectly and where, if we changed even one, the whole thing would stop working.

Despite all the writing I have done, I still find it hard to describe the sensation this evokes for me. This is our marvellous universe! It works in this wonderful way and we have been able to figure it out. How delightful!

I was so enthusiastic about general relativity that I did my doctorate studying how measurements of the speed of space-time's expansion might inform our effort to merge GR with another fundamental theory, quantum mechanics (see our special, page 28). At the time, I understood, in mathematical terms, the challenges of merging these two theories. Modifying general relativity without ruining what makes it special seems virtually impossible, and the same is true of quantum physics.

After I completed my doctorate, I took almost 15 years off from trying to reckon with this conflict. When I returned to it recently as I worked on my next book, *The Edge of Space-Time*, I found that general relativity ages like fine wine – and so does the quantum gravity problem. What I more deeply understand now are the conceptual challenges involved. General relativity may eschew absolute space and time, but it still calculates with certainty. Quantum mechanics, however, deals in probabilities and comes with guaranteed uncertainty. And yet, somehow, a world that feels certain – at least physically, if not politically – emerges for us to live in. I have a better gut feeling now for why this disagreement is so fascinating and inspiring.

I am so grateful that, at an early stage, I learned the fundamentals that would allow me to grow old with this problem. It is a reminder that thinking about our material conditions is more than worrying about money and whether leaders will make social policies that serve all of us. Our material conditions are also the result of being in space-time, being scientists and community knowledge holders, and being lifelong learners who never see our relationship with space-time as complete. ■

This column appears monthly. Up next week: Graham Lawton

Living giants

Mitch Epstein
Skira Editore

GNARLED, wild and majestic: these two very different trees in California form part of Mitch Epstein's quest to photograph ancient forests across the US.

The photographer's *Old Growth* project took shape in the summer of 2020, when he learned that there were rare pockets of old-growth forests in Western Massachusetts – those that have grown for hundreds, or even thousands, of years. One-third of the world's forests today are old-growth, but since 1990, their range has decreased by 81 million hectares.

Over the next four years, Epstein travelled to remote locations across the US to find ancient native trees and document what we stand to lose through climate change. He captured firs, oaks, birches and maples, including this denizen of the Ancient Bristlecone Pine Forest (far left), taken in California's White Mountains in 2022, and this towering sequoia (near left), snapped on the Congress Trail in 2021 in the state's Sequoia National Park.

The photographer said the project was a departure for him. "I didn't think that I could bring something new to so-called nature photography," he said in an interview included in his new book *American Nature*, which brings together photographs of his work. "Maybe part of my decision to photograph *Old Growth* was this realisation: that there is now no wilderness that hasn't been touched by humans in some way, even if it's not immediately obvious."

Alison Flood

Dreams of the powerful

Exposing the origins of the outlandish and downright scary dreams of tech billionaires makes for a disturbing but important book, finds **Jeff Hecht**

Book
More Everything Forever
Adam Becker
Basic Books
On sale 22 April (US); 8 May (UK)

WITH Elon Musk and his minions stomping through Washington government offices like Godzilla in Tokyo, and other tech multi-billionaires having gained US President Donald Trump's ear, the super-rich are getting super-scary.

Science writer Adam Becker shares his disconcerting analysis in *More Everything Forever: AI overlords, space empires, and Silicon Valley's crusade to control the fate of humanity*. He finds would-be rulers of the universe with egos the size of planets and impossible, science-fictional dreams of endless growth at infinite speed across the universe.

Sometimes even scientifically trained fans of such dreams can take the science in sci-fi too seriously. Take physicist Gerard K. O'Neill. Soon after the Apollo moon landings, he detailed plans to expand into space by building giant cylindrical habitats to house a million people in stable Earth orbit near the moon. The book containing this vision, *The High Frontier*, inspired young space enthusiasts – including Amazon founder Jeff Bezos.

O'Neill's plan had some big flaws. The technology was far beyond even today's NASA, and long-term exposure to space radiation outside Earth's protective magnetic field would have been lethal to humans and electronics.

Today, such space plans look less improbable. But other tech-fuelled dreams have developed alongside them. The technology advances of recent years have fed a stock market boom and given Silicon Valley huge political as well as economic clout.

Becker is rightly wary of vocal advocates of artificial intelligence, particularly Sam Altman. As CEO of OpenAI, he launched ChatGPT and leapt into the multi-billionaire club. Becker quotes him as saying "this technological revolution is unstoppable", and that he sees AI as taking over all services and manufacturing.

Altman is all over the map. On one page, he sounds like a libertarian, welcoming an AI conquest of the economy as something that will make us all rich and happy. On another, he's cautious, warning we will need a strong government to protect "the environment, human rights, etc".

"Tech advances have fed a stock market boom, and given Silicon Valley huge political as well as economic clout"

For the tech billionaires, Becker writes, "the future is straight out of science fiction: people's minds uploaded into computers to live for eternity in a silicon paradise, watched over benevolently by godlike AI; a ceaselessly expanding empire spanning the stars, disassembling planets, and consuming galaxies".

Their dreams reflect all this, with Bezos wanting a trillion people living in space "to enable a future of perpetual growth, lest we 'stagnate' here on Earth", and software engineer turned venture capitalist Marc Andreessen keen to see an eternally triumphal "techno-capital machine" to conquer the cosmos with AI and the power of entrepreneurship.

It is almost enough to make Musk's obsession with colonising Mars to save humanity from extinction seem like a cautious exercise, until you read Becker cite Musk on X arguing that the "true battle is: Extinctionists who want a holocaust for all of humanity versus Expansionists who want to reach the stars and Understand the Universe".

The philosophers and ethicists who act as soothsayers for the tech bros can have even more bizarre ideas. Some advocate "effective altruism", which involves making lots of money to donate to charity (the idea behind Sam Bankman-Fried's creation and looting of a cryptocurrency exchange that got him 25 years in prison).

In Becker's estimation, William MacAskill, a philosopher at Oxford University and a co-founder of the effective altruism and "longtermism" philosophies, seems to believe that the best thing we can do for future humanity is to fill the universe with as many people as possible.

More Everything Forever is a disturbing and important book. Becker's most chilling message for me is that the tech billionaires don't understand one key fact: what's inside the singularity they dream of is a black hole. To put it simply, the world is going to become unfathomable and incomprehensibly dangerous. And they just don't get it.


SPACEX

A future human base on Mars, as imagined by Elon Musk's SpaceX

Jeff Hecht is a writer based in Auburndale, Massachusetts

Making waves

Why is saying no so hard? **Alison George** explores a fascinating book with some novel ideas

Book

Defy
Sunita Sah
Blink Publishing (UK)
One World (US)

MARTIN PARR/MAGNUM PHOTOS

Whether you are at the hairdresser's or at work, the ability to say no is always crucial

WE'VE all done it. Some of us do it all the time, in situations both trivial and serious. We say "yes" when we shouldn't, or fail to say "no" when we should, nodding approvingly when the hairdresser has done a terrible job, caving in to a zealous salesperson or staying silent when a colleague is being undermined in a work meeting.

That is to say, we go along with things, even when it goes against our true values. Part of this comes down to being human. To function as a social species, a degree of conformity and compliance is necessary. But it also does us a disservice when we consistently fail to stand firm in our convictions and comply under pressure, even if our internal voice is telling us otherwise.

This is the subject of Sunita Sah's book *Defy: The power of no in a world that demands yes*. Sah, a former doctor in the UK and now an organisational psychologist at Cornell University in New York state, argues we can all learn how to say no when it matters most. This is a skill, not a character trait, she says.

Sah's work has uncovered some of the psychological factors that prompt us to conform. One that many of us will recognise is the uncomfortable feeling when we worry that not complying with another person's wishes could be interpreted as a signal of distrust. This leads us to worry more about offending the other person than doing what we think is right.

Sah calls this "insinuation anxiety", and her studies shed light on how this changes our behaviour. For instance, when a salesperson or doctor reveals they will be paid an incentive if we take the advice that they are recommending, we trust them less – yet, counterintuitively, we are more likely to follow their advice because of the anxiety of not wanting to insinuate that they are biased or untrustworthy.

This form of interpersonal stress has important real-world consequences. Insinuation anxiety, says Sah, may be one reason why only a fraction of healthcare workers or airline personnel will speak up if they spot an error made by a colleague.

But Sah argues that tuning in to the uncomfortable feeling of insinuation anxiety is crucial if we are to learn how to fight our internal pressure to conform. "It's our warning sign," she writes.

It can also help to be aware of another potential factor Sah's research has uncovered: the paradoxical "kicking yourself" effect. If you are swayed to make a decision against your better judgement, you might think that this would alleviate feelings of guilt and responsibility if the outcome was bad. In fact, she writes, people feel more culpable if they think they should have known better than to follow bad advice.

Of course, this subject matter leads Sah to difficult and uncomfortable places, and she doesn't shy away from them in *Defy*. For example, she delves into the nuances of the infamous Milgram experiment carried out in the 1960s to investigate whether the claim of "just following orders" – the constant refrain during the Nuremberg trials of former Nazi officers – was a psychological reality outside such regimes.

She also looks into the Challenger space shuttle disaster, caused by a failure of a crucial component of the spacecraft, the O-rings, where the concerns of the engineers who manufactured the parts were overruled.

But if a rallying cry for the power of saying no when it really matters conjures up images of being angry and confrontational, superhuman or heroic, think again.

"It isn't only for the brave, or the extraordinary," writes Sah. "It has a quieter, small-scale side – which can have enormous impacts on our lives and the lives of those around us."

New Scientist *recommends*

Jeremy Hsu
Reporter
New York

An overcast and chilly Sunday didn't deter me, my family and thousands of others from queueing around New York's Union Square for the chance to handpick a bouquet of 10 colourful tulips.

The second annual **Tulip Day** organised by Royal Anthos, a Dutch trade organisation, was free with registration, though tickets vanished as fast as they would for a Taylor Swift concert.

It was a surprisingly cheery experience, picking spring flowers at an event sponsored by the European Union, even as relations look

CRAIG T FRUCHTMAN/GETTY IMAGES

increasingly fraught between the US and EU.

Politics was also on my mind as I read **Nazi Billionaires** – a look into the history of brands like BMW and Porsche by journalist David de Jong. He details how industry bankrolled Hitler's Nazi party, shrugging off the demise of democratic governance as they profited from crony capitalism and the use of forced and slave labour.

In other words, don't expect billionaires to save democracy.

The TV column

Same as it ever was? *Black Mirror*'s new season is a mixed bag, ranging from a sublimely plotted romp to one of the worst episodes to date. And it's still playing fast and loose with its sci-fi concepts, finds **Bethan Ackerley**

Bethan Ackerley is a subeditor at *New Scientist*. She loves sci-fi, sitcoms and anything spooky. Follow her on X @inkerley

TV
Black Mirror
Charlie Brooker
Netflix

NICK WALL/NETFLIX

Elena Tulaska (Milanka Brooks) in *USS Callister: Into Infinity*

WHEN *Black Mirror* began in 2011, it was easy to describe: a British horror anthology series about technology. Over time, that description has become fuzzier. It no longer feels very British. It's not always horrifying or tech-inclined. Sometimes, it's not even TV: in 2018, an interactive film called *Black Mirror: Bandersnatch* let viewers control the life of troubled programmer Stefan (Fionn Whitehead).

Now in its seventh season, *Black Mirror* has metamorphosed again. It's no longer a pure anthology, with two new episodes serving as sequels to *Bandersnatch* and season four's *USS Callister*, respectively. So what is *Black Mirror* these days?

Let's talk about those sequels for a moment. The first, *Plaything*, is set in a near-future where Cameron Walker (Peter Capaldi) is being interrogated on suspicion of murder. While working as a writer for *PC Zone* in the 1990s, he visited Tuckersoft, the company at the heart of *Bandersnatch*, where Colin Ritman (Will Poulter) was designing a new game.

Fans of *Bandersnatch* seeking revelations about Stefan will be left wanting, as *Plaything* doesn't overtly intersect with the film much. That said, it is pleasantly meta – *Black Mirror* creator Charlie Brooker started out at *PC Zone* himself – and certain events hint that Cameron is experiencing something similar to Stefan, but here the viewer can't influence the narrative. It's a brilliant move, and compelling for anyone who spent hours chasing *Bandersnatch*'s various endings, but less so for viewers coming to the episode afresh.

> **"*Into Infinity* is so much fun that it makes the flaws of the rest of the season all the plainer"**

The other sequel is far more straightforward and satisfying. In *USS Callister*, Robert Daly (Jesse Plemons), the disgruntled creator of an online game called *Infinity*, patched digital clones of his colleagues into a *Star Trek*-esque bubble universe where he could abuse them at will. After defeating Daly, Nanette Cole (Cristin Milioti) and her crew flew off into the sunset in search of their next adventure.

But when we rejoin them in *USS Callister: Into Infinity,* things aren't looking so rosy. The game has become increasingly expensive to play, forcing the crew to rob players simply to keep their ship running. And while those they target can easily respawn when killed, for the clones, death in *Infinity* is real.

Into Infinity is a tightly plotted romp that proves Brooker was right to rip up the rulebook and write a sequel. It's so much fun that it makes the flaws of the rest of the season all the plainer. *Eulogy* and *Hotel Reverie* are romantic instalments with plenty of heart but are ultimately forgettable. *Bête Noire* is better, oozing with nastiness; *Common People*, meanwhile, is one of the worst instalments of *Black Mirror* to date.

So what does this new season tell us about *Black Mirror* in 2025? That despite many reinventions, it remains a mixed bag.

One early, enduring criticism of the series was that its sci-fi concepts are shallow and poorly explored – "what if phones, but too much?", as writer Danny Lavery once put it. This certainly remains the case for some of the weaker new episodes – but others are as thought-provoking and grimly entertaining as the show ever has been. The more things have changed, the more they have stayed the same.

Sounds like something straight out of *Black Mirror.*

Bethan also recommends...

TV
Cunk on Earth
Charlie Brooker
BBC iPlayer/Netflix

Philomena Cunk (played by Diane Morgan) was born as a talking head in Charlie Brooker's Weekly Wipe*, and she deserves to be as immortal as Alan Partridge.*

Book
Screen Burn
Charlie Brooker
Faber

I compulsively read this compendium of Charlie Brooker's TV columns as a teenager, and look at me now. Let that be a warning to parents everywhere.

Editor's pick

A tale of microdosing weight-loss drugs

29 March, p 33

From Nic Marks, Salisbury, Wiltshire, UK

I have been a classic middle-class microdoser when it comes to the weight-loss drug Wegovy. For nine months, I took 0.5 milligrams a week (instead of the recommended maintenance dose of 2.4 mg) and lost over 20 kilograms. It was amazing. However, I became increasingly grumpy, so I decided to stop for a while. Ten days later, I was sitting reading when I felt a strange sensation; it was as if the lights had gone back on. My mood completely lifted. At lunch, my wife said it was the first time she had heard a lilt in my voice for months. I have been off Wegovy for over two months and have put on only 2 kg, and my mood is back to normal. It has definitely been a net positive for me, but the short and long-term side effects, including mood, need better investigation.

On the idea of storing carbon by rewilding

29 March, p 39

From Richard Jefferys, Berkhamsted, Hertfordshire, UK

It is suggested that rewilding with large herbivores could sequester a lot of carbon in soil. But does this work long-term? I worry that soil contains a host of bacteria that love to degrade carbon to carbon dioxide. And ruminant herbivores, among the rewilding animals suggested, emit a lot of methane.

From Cheryl Hillier, Cribyn, Dyfed, UK

Finally, an acknowledgement of the power of nature to absorb/build carbon – but will we allow it to? Growing in monocultures at the expense of everything else poses the greatest threat to biodiversity, food and water security and resilience to flood, fire and drought. If we stop and devote all farmland to sustainable practices, all food then has the potential to be healthy and grown in ways that sequester carbon, restoring biodiversity and health to the systems we rely upon. Rewilding and sustainable farming aren't mutually exclusive, so why not do both?

Can new maths help us with quantum collapse?

22 March, p 12

From John Bell, Berkhamsted, Hertfordshire, UK

Your article on the mathematical breakthrough bringing together three sets of equations relating to particles and fluids ends with a line saying that the implications of the work aren't yet understood. With the techniques being grounded in Richard Feynman's work on quantum field theory, and with the obvious parallels with particles vs fluids and waves, I can't help but wonder whether this work might help model the turning point in quantum physics, when wave functions collapse and classical physics emerges.

Try this formula for the perfect boiled egg

Letters, 22 March

From Seán Kelly, Leighton Buzzard, Bedfordshire, UK

I have been reading with amusement the discussion on how to cook the perfect boiled egg. *New Scientist* put the matter to bed for me when the Last Word (13 June 1998) published a formula from reader Charles Williams for this. It went as follows: Cooking time = $(m^{(2/3)}) \times [\ln(2 \times (t - 100)/(45 - 100)]/c$, where t = initial egg temperature in celsius; m = mass of egg in grams and c is a constant. Having just started keeping hens, which don't produce uniformly weighted eggs, I experimented to determine the value of c (3.758) that resulted in eggs boiled to the doneness appreciated by my wife and me. The resulting chart is displayed on our fridge door for ready reference.

There are more ways to keep dementia at bay

15 March, p 14

From Geoff Harding, Sydney, Australia

Surely additional years at school or in higher education wouldn't be the sole means of building the cognitive reserve now regarded as a means of postponing the onset of dementia. A number of trades requiring an apprenticeship and continual accumulation of technical skills and know-how, perhaps over an entire lifetime of employment, could be equally beneficial and often far more challenging and useful than some academic pursuits. The important factor is to use the brain, continue to learn and apply that knowledge for personal benefit, and perhaps to teach others.

From truly ancient folk myths to bible stories

15 March, p 34

From Bryn Glover, Kirkby Malzeard, North Yorkshire, UK

I was particularly struck by the idea in Laura Spinney's article that some folk myths may date back as far as 60,000 years when, it is believed, a few *Homo sapiens* individuals made their way out of Africa. I have often wondered whether the tale of Moses crossing the Red Sea had its origins in the journey taken by these early ancestors, presumably across the modern Bab-el-Mandeb Strait.

Fighting fatigue isn't always possible

15 March, p 30

From Lyn Williams, Neath, West Glamorgan, UK

An important point regarding bodily energy levels is missed. If things aren't going well in our lives, we will feel depressed. The level of which will depend on how bad the situation is. In this state we feel tired and maybe want to sleep more than usual. We can't feel full of energy while like this.

Tentacled octopoid robot may be the perfect design

Letters, 15 March

From Robert Peck, York, UK

Brian Horton makes a good point about the need for versatility within a single robot design, but there is no reason a specifically human form is needed for this. A quadruped with a many-armed torso, or some sort of tentacled octopoid design, could serve just as well. As could a robot composed of reconfigurable jointed modules; I designed one for my thesis, able to change shape for varying tasks.

Possibly the oldest code in the known universe

8 March, p 34

From Steve Field, Ashford, Kent, UK

I have a theory that the oldest computer code is found in the program on which our simulated universe runs. Glitches caused by incompatible code lead to some unexplained events commented on in your pages. Minor glitches include mislaying 95 per cent of the universe and incompatibility of relativity and quantum physics. Major ones include the prevalence of odd socks.

Want to get in touch?

Send letters to letters@newscientist.com; see terms at newscientist.com/letters

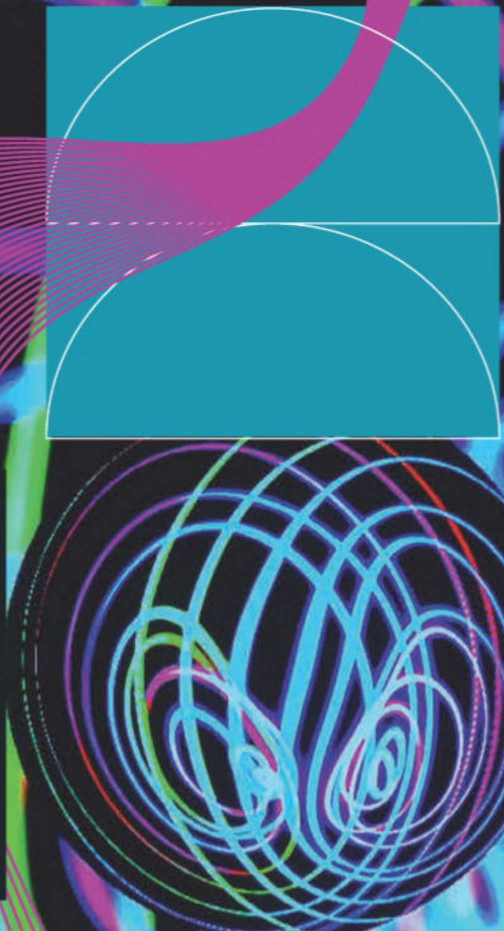
Letters sent to New Scientist, 9 Derry Street, London, W8 5HY will be delayed

For the record

When iron and sulphur occur in "reduced form", they have gained electrons (29 March, p 18).

Features Cover story

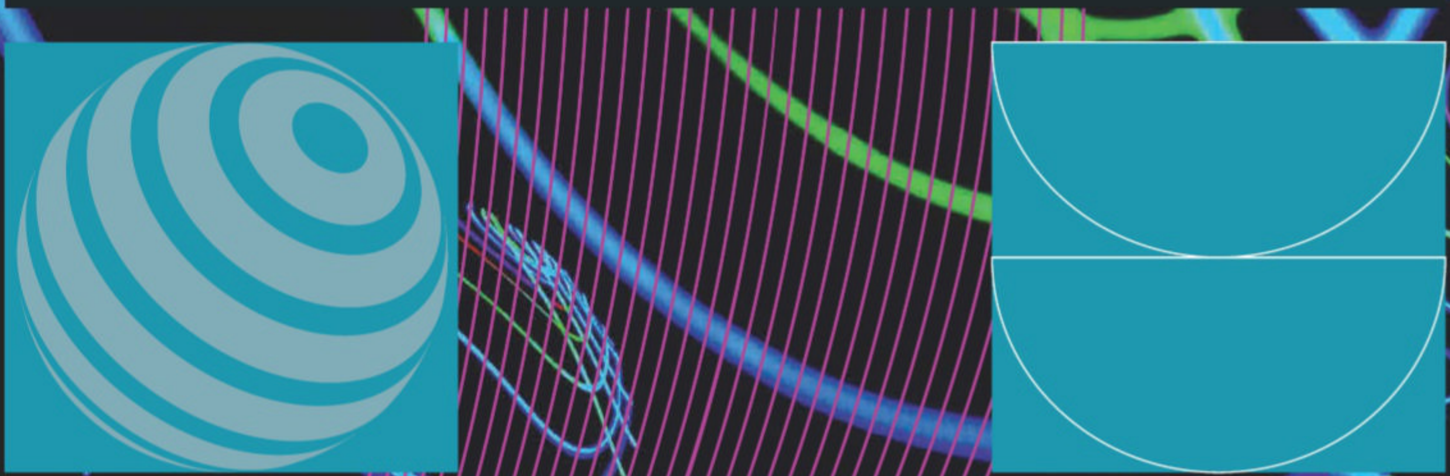
OUR QUANTUM CENTURY 100

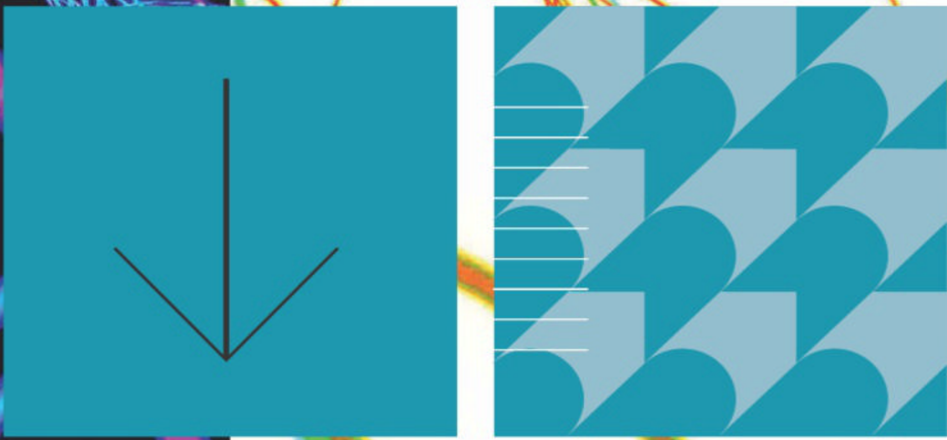


ONE hundred years ago this June, a 23-year-old physicist travelled to the tiny, windswept island of Helgoland in the North Sea. Werner Heisenberg's objective was to soothe his hay fever – the island is so weather-beaten that it has almost no vegetation. But in his splendid isolation, he scribbled a set of calculations that set the stage for the development of quantum mechanics. This year, people will gather around the world – including on Helgoland itself – to celebrate the wild ride that this reality-shaking idea has taken us on.

Quantum theory has much richness to it (see "What is quantum theory?", page 30), even if it is famous for one thing above all else: being weird. But it is also worth pausing to take stock of its enduring majesty and mystery, as we do over the next 11 pages.

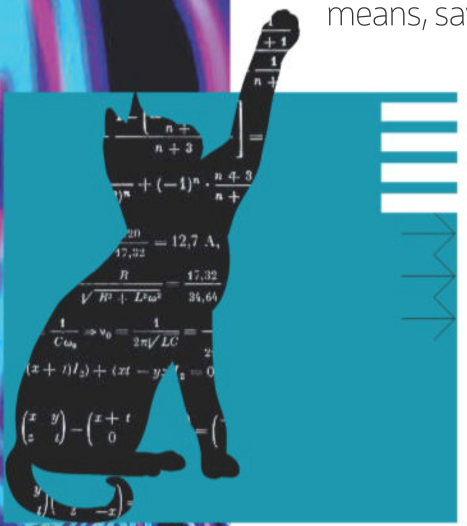
To begin, physicist Carlo Rovelli takes us back to the birth of the theory and hails one of its unsung founders (see right). Since then, quantum theory has transformed many aspects of our lives – a process that quantum computers will continue, as we explore on page 32. At the same time, profound questions remain about what quantum theory means. It suggests the deepest layers of reality function in ways that defy comprehension – but as we explain on page 35, new experiments may finally help us grasp what perhaps our greatest scientific theory has been trying to tell us for the past century.





QUANTUM THEORY'S UNSUNG HERO

Accounts of the birth of quantum mechanics often overlook one of its key protagonists – and this has generated persistent confusion over what the theory means, says physicist **Carlo Rovelli**



UNSPLASH

THE story of the birth of quantum mechanics is often told, but not always correctly, in my opinion. Introductory quantum physics classes focus on the famous equation written by Erwin Schrödinger in 1926, which describes quantum waves. I think the emphasis on these waves has generated a confusion that persists today. The birth of quantum theory happened a year earlier, largely in the work of Max Born and his collaborators. And I like to draw attention to this point not just to give Born deserved credit, but also because I think the emphasis on Schrödinger's waves is responsible for today's confusion about what quantum phenomena tell us about reality.

Let me start from the beginning. It is often said that quantum physics arrived as a surprise at a time when physicists thought they had figured out all the basic laws of nature. There never was such a time. At the end of the 19th century, physicists were confused about plenty of basic things.

This is why nobody paid much attention when, in October 1900, Max Planck came up with a simple but unjustified equation in trying to make sense of certain obscure experimental measurements of the electromagnetic radiation inside hot cavities. The equation was $E = hv$. It connects the energy (E) and the frequency (v) of the radiation via a totally new constant (h), now known as Planck's constant. This constant, we now know, sets the scale of quantum phenomena.

It was Albert Einstein, five years later, who saw what this equation could mean: light is made of particles, or "quanta of light", each having energy $E = h\nu$. This didn't square with what was considered empirically established at the time: that light is a wave. A young postdoctoral researcher today raising a suggestion like Einstein's, so contrary to established views, wouldn't be taken seriously by anybody.

Nor, in fact, was Einstein. He became nearly instantly famous for relativity, but his "quanta of light" were considered outlandish. A recommendation letter to the Berlin ministry urging that a new position be opened for him stated that the young Einstein was a genius and should be excused for silly ideas about quanta of light. But his quanta predicted a physical effect that turned out to be real, and earned him his Nobel prize.

Einstein's paper on the subject opens with the words: "It seems to me that [numerous] observations... are more readily understood if one assumes that the energy of light is discontinuously distributed in space". Note the wonderful initial, "It seems to me". Ordinary people have certainties. Genius hesitates.

Quantum theory's next steps came from the work of Niels Bohr in Denmark. Bohr was concerned with the structure of atoms, which emit light at specific frequencies that can be carefully measured in the lab. Bohr realised that these specific frequencies could be understood if electrons orbited the atomic nucleus only on special, "quantised" orbits. Like Einstein's quanta of light, these orbits could only have special, quantised energies. Electrons would then (mysteriously) "jump" from one orbit to the other, emitting quanta of light. These are the famous "quantum jumps".

To most physicists, this sounded like black magic. But it worked: with these daring assumptions, Bohr could predict the frequencies of the emitted light correctly. Something of the mystery of the atom appeared to be unravelling.

Bohr became a recognised figure. He created an institute in Copenhagen where the best minds of the younger generation began to gather, trying to fully unravel the physics of the atom. Among these visitors was Werner Heisenberg. In the summer of 1925, inspired by Bohr's ideas and taking refuge from a violent attack of hay fever, the 23-year-old Heisenberg spent a few days of solitude on the wind-scorched island of Helgoland, in the North Sea.

After obsessive and feverish days of intense calculations, mixing up confused ideas, Heisenberg produced an acrobatic calculation that would change the direction of science. He treated the position of an electron not as a single variable, but rather as a table of › numbers, with rows and columns indicating the initial and final orbit of a quantum "jump".

Years later, perhaps romanticising, he described himself on the island with these words: "It was around three o'clock in the morning when the results of my calculations were before me. I felt profoundly shaken. I was so agitated that I could not sleep. I left the house and began walking slowly in the dark. I climbed on a rock overlooking the sea at the tip of the island, and waited for the sun to come up..."

AN ORACULAR EQUATION

Back at his home university in Göttingen, Germany, he gave the calculation to his boss, Max Born. Out of Heisenberg's messy calculation, Born saw the key to the new physics: physical quantities aren't described by simple variables. They must be described by more complicated mathematical quantities that "do not commute". This means the multiplication of two quantities gives a different result depending on which comes first. Born divined that the position X and the momentum P of an electron satisfy the fundamental equation $XP - PX = ih/2\pi$. In this equation, h is the constant that Planck had introduced 25 years earlier – and i is the imaginary unit, the square root of -1.

This obscure oracular equation is the core of quantum theory. It means that if we first measure the position of a particle and then its velocity, we can obtain a result that is different from measuring velocity and position in the opposite order. Position and velocity, therefore, aren't properties of an electron that are exactly simultaneously determined.

Born sent Heisenberg's article to a scientific journal in Heisenberg's name. Then, with the help of Pascual Jordan, a mathematically brilliant assistant also in his early 20s, he published the founding paper of quantum theory, with the new equation, over-generously attributing all the credit to Heisenberg. Many further clarifications and a spectacular number of applications awaited the theory in 1925. But in the articles of Born, Jordan and Heisenberg, quantum theory was already in place.

Max Born, in my opinion, deserves the credit for the discovery of quantum theory more than anybody else among the many scientists involved in this grandiose intellectual adventure. He introduced the expression "quantum mechanics". He divined the founding equation $XP - PX = ih/2\pi$. He is the unsung hero of quantum theory.

A few months later, Wolfgang Pauli showed that not only the frequencies but also the intensities of the light emitted by the atoms could be computed from first principles with the new theory. In a letter to his old friend Michele Besso, Einstein wrote that: "The most interesting theorisation of recent times is that of Heisenberg-Born-Jordan on quantum states: a calculation of real witchery."

For his part, Bohr, the old master, would recall years later: "We had at the time only a vague hope of [being able to arrive at] a reformulation of the theory in which every inappropriate use of classical ideas would be gradually eliminated. Daunted by the difficulty of such a programme, we all felt great admiration for Heisenberg when, at just twenty-three, he managed it in one swoop." Well, Heisenberg... with a little help from his friends. But, perhaps unfortunately, this isn't the end of the story.

First, another kid in his early 20s, Paul Dirac, equally realised that Heisenberg's tables were non-commutative variables. He constructed an abstract theory that turned out to be the same as that of the wizards of Göttingen.

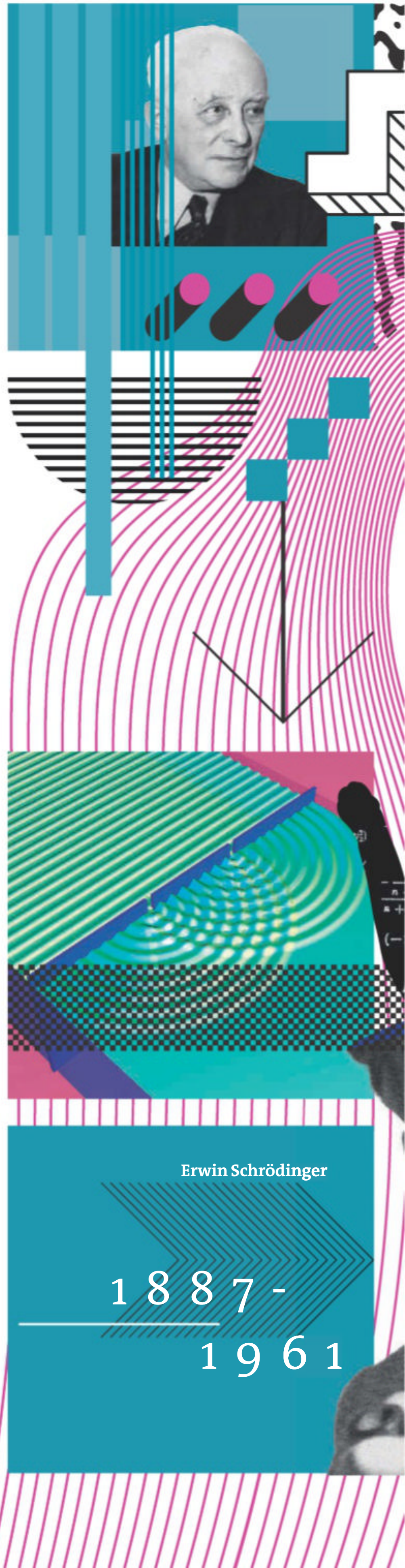
Then trouble came. Schrödinger arrived at the same results as Pauli using totally different ideas. His weren't obtained in a university department either: the story goes that he was on a retreat in the Swiss mountains with a secret lover.

Schrödinger developed an idea introduced in the PhD thesis of the young physicist Louis de Broglie. The thesis, which Einstein had pointed out to him, explored the obscure possibility that electrons – considered at the time to be particles – might also be waves, like Einstein's quanta of light. Schrödinger wondered which equation would be satisfied by these

WHAT IS QUANTUM THEORY?

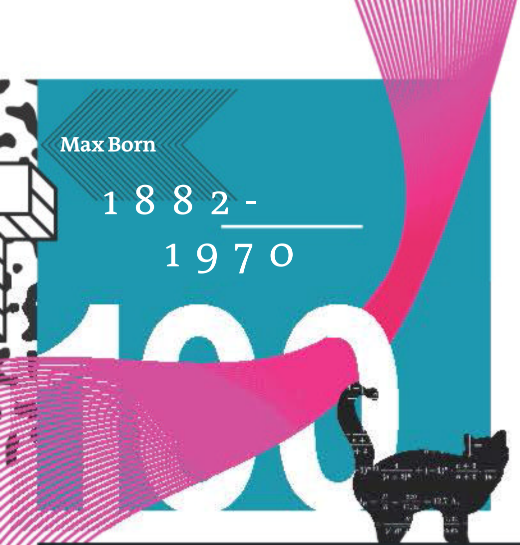
THE founding principle of quantum theory isn't too complicated. To get your head around it, imagine how you might turn the volume knob on an old-fashioned stereo and hear the sound get gradually louder. Quantum theory says that the properties of particles, such as their energy, don't vary in this way. Instead, they can only take on certain discrete values. Think more of turning up the heating on a thermostat, moving from one degree to another with no transition between. This assumption about how particles work turns out to be a far superior way to explain reality (see main stories).

The problems start with how the theory works in practice. It provides a probability for what you will find when you measure a particle, but it says nothing about what it is doing beforehand. How to interpret this has confused us from the start. And over the years, we have also discovered that quantum particles behave in deeply strange ways. They sometimes seem to act more like waves, for instance. Pairs of them can be entangled, meaning they can apparently influence each other's properties even when separated by vast distances. They can also adopt a superposition, being in two places or taking two paths at once.



Erwin Schrödinger

1887-1961



waves, and guessed it. Then, using it in spare moments during his romantic break, he derived the same results regarding the atom that Pauli had obtained with the Göttingen group's theory.

The idea of an electron being just a wave was so simple that it threw the Göttingen group and their esoteric speculations on non-commuting quantities off balance. It seemed like Heisenberg, Born, Jordan and Dirac had built an obscure theory only because they had taken the long and winding road. Things could be made much simpler: the electron is a wave. Waves are easy to visualise. Schrödinger appeared to have triumphed.

THE LIFE AND TIMES OF QUANTUM THEORY

The seeds of quantum theory were sown by Albert Einstein and others as early as 1905. But the theory came together properly **100** years ago in 1925 – and has exerted its influence ever since, as this timeline shows.

› **1905** **Riffing on earlier work by Max Planck, Albert Einstein suggests that light is made of particles with certain energies. These "quanta of light" were an early step on the road to quantum theory.**

› **1913** **Niels Bohr produces a quantum description of the atom in which electrons can only exist in certain orbits with fixed energies.** ›

ALAMY; SPL

But his victory was short-lived. Heisenberg soon realised that the clarity of Schrödinger's waves was a mirage. A wave spreads out, an electron doesn't: when an electron arrives somewhere, it arrives at a single point. The discussion became lively, then virulent. Heisenberg was cutting: "The more I think about the physical aspects of Schrödinger's theory, the more repellent I find it. When he [Schrödinger] writes about the visualization of his theory being probably not completely correct, it is tantamount to saying that it is idiotic". Schrödinger tried to retort wittily: "I cannot imagine an electron leaping about, here and there, like a flea."

NURTURING ILLUSIONS

Heisenberg was right. Wave mechanics is no clearer than the non-commutative abacus of Göttingen. Years later, Schrödinger, who was to become one of the most acute thinkers on the strangeness of quanta, recognised defeat. "There was a moment," he writes, "when the creators of wave mechanics [that is, himself] nurtured the illusion of having eliminated the discontinuities in quantum theory. But the discontinuities eliminated from the equations of the theory reappear the moment the theory is confronted with what we observe."

Born was awarded the Nobel prize much later, in 1954, and only for "the statistical interpretation of the wave function". Why so late? Why was he not recognised for his monumental 1925 contribution? He had already arrived at full quantum mechanics, its basic formula $XP - PX = ih/2\pi$, and he had uncovered this statistical interpretation before Schrödinger's wave function. Maybe Pascual Jordan's Nazi sympathies played a role: he co-authored the two papers where quantum mechanics is defined, and after the second world war, it might have been difficult to award a Nobel prize to him.

In a 2023 paper I wrote with the historian of science John Heilbron, we analysed the historical developments that led to quantum theory, and we observed that in the history of science, like always in history, the evaluation of the past evolves as ideas change in the present.

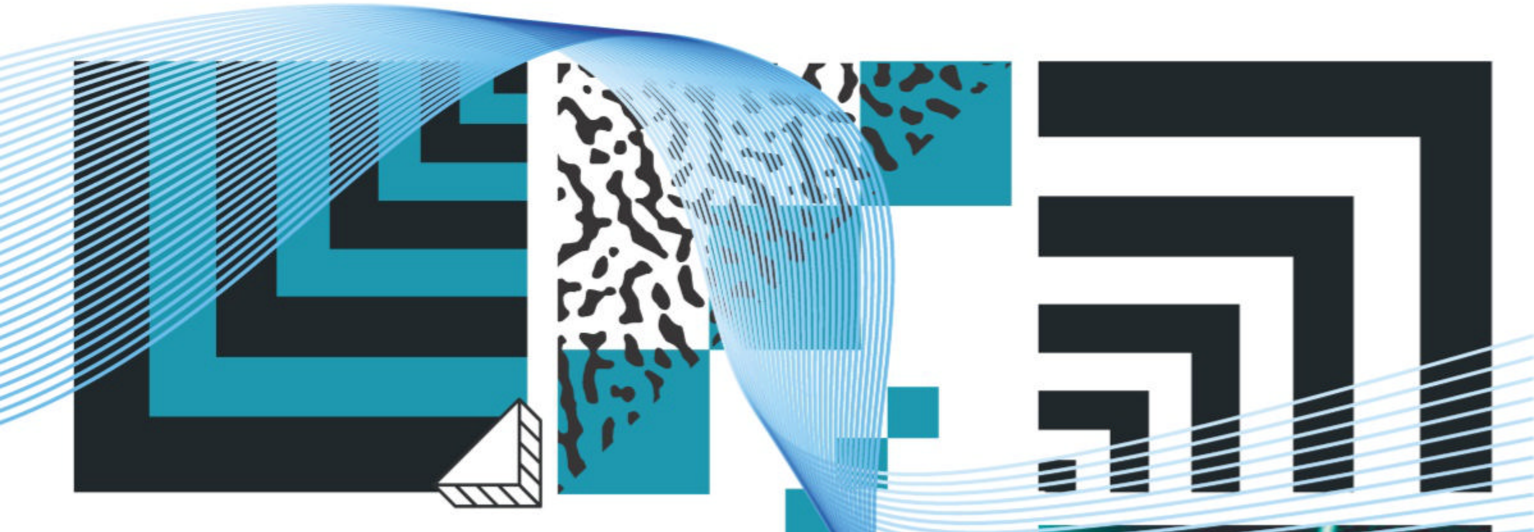
What quantum phenomena tell us about reality is still debated (see "The meaning of quantumness", page 35). There are various interpretations. I think that Schrödinger's waves are only a mathematical representation of the information that a physical system has about another. This reading of quantum phenomena is called "relational", because it emphasises that we can only describe how systems affect one another, not how they are in isolation. In other interpretations, such as "QBism", quantum states only code our own knowledge of a system.

In light of these ideas, it is clear to me that Schrödinger's waves obscured, rather than clarified, the theory developed by Göttingen's wizards and Dirac. It misled the community into viewing quantum theory as a revelation about mysterious waves (or mysterious "quantum states"), instead of reading it in the straightforward Göttingen way: a theory of the probabilities of the manifestations of a system to any other system.

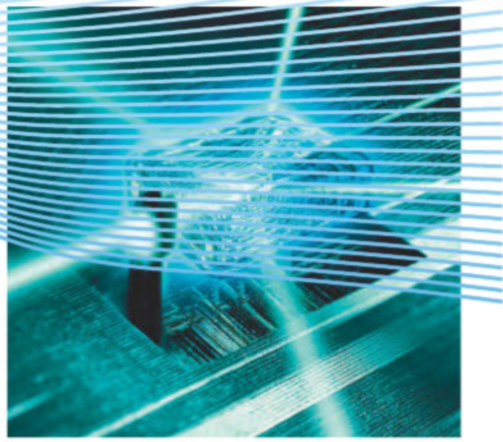
I think what quantum phenomena tell us is that the world is genuinely probabilistic and granular at the scale fixed by the Planck constant, and that reality is constituted by manifestations of physical systems to one another. This is captured in the words of Niels Bohr: "In quantum physics the interaction with the measuring apparatus is an inseparable part of the phenomenon. The unambiguous description of a quantum phenomenon is required in principle to include a description of all the relevant aspects of the experimental arrangement."

Little about this idea needs to be changed, a century later: all that is required is to replace "the measuring apparatus" with "any other physical system" the object is interacting with. The world is the ensemble of ways that physical systems affect one another. This is what quantum physics seems to me to be about. That is quantum mechanics as Max Born, the scientist who named it, had conceived it.

Carlo Rovelli is a physicist at Aix-Marseille University in France and the author of *Helgoland*



OUR QUANTUM-POWERED FUTURE



Of all the novel quantum technologies under development, quantum computing is the most likely to transform science and society. But how exactly will it do that? **Karmela Padavic-Callaghan** investigates

QUANTUM physics gets a bad rap. The behaviour of the atoms and particles it describes is often said to be weird, and that weirdness has given rise to all manner of esoteric notions – that we live in a multiverse, say, or that the reality we see isn't real at all. As a result, we often overlook the fact that quantum physics has had a real effect on our lives: every time you glance at your smartphone, for instance, you are benefiting from quantum phenomena.

But the story of what quantum theory is good for doesn't end there. As our mastery of quantum phenomena advances, a new of crop of technologies designed to harness them more directly promises to have a huge impact on science and society. While quantum teleportation and quantum sensing sound exotic and intriguing, the technology that holds the most transformative potential is the one you have probably already heard of: quantum computing.

If you believe the hype, quantum computers could accelerate drug development, discover revolutionary new materials and even help mitigate climate change. But while the field has come a long way, its future isn't entirely clear. Engineering hurdles abound, for starters.

And what often gets lost in the race to overcome these challenges is that the very nature of quantum computing makes it difficult to know exactly what the machines will be useful for. For all the bombast, researchers are quietly confronting the same existential question: if we could build the quantum computer of our dreams tomorrow, what would we actually do with it?

It is easy to overlook the ubiquity of quantum physics in modern technology because of the scales at which it operates. Infinitesimally small things like particles exhibit quantum effects, such as sometimes behaving like waves, that don't persist in macroscopic stuff. While an orange, for example, is made of atoms, which are quantum, you cannot cajole a piece of fruit to become a wave as you might with a single quantum particle. But when it comes to the many gadgets that we now take for granted, the quantum character of the individual electrons within them is crucial.

Take the transistor, the basic building block of modern electronics. These nanometre-sized semiconductors are how we control the flow of electrons inside of microprocessors. We make them by changing the geometry and makeup of silicon, stacking it in layers and spiking those layers with atoms of other elements. But it would be impossible to make an electron do anything in this way if you didn't know that it sometimes behaves like a wave, which is about as quantum a behaviour as can be.

It is no exaggeration to say that the seemingly abstruse theory of quantum physics has transformed the way we live. Without quantum

› **1919** Physicist Hendrika Johanna van Leeuwen writes a thesis proposing that magnetism is also a quantum mechanical phenomenon.

› **1925** On the windswept island of Helgoland, Werner Heisenberg carries out a calculation that treats the electron's characteristics not as single values, but as tables of values. In this, his supervisor, Max Born, spots a key truth of quantum mechanics (see "Quantum theory's unsung hero", page 29).

› **1926** Erwin Schrödinger develops an alternative quantum framework that paints electrons as waves using a mathematical construct called the wave function. ›


SPL

"IN THE LAST FIVE YEARS, THERE HAVE BEEN REMARKABLE ADVANCES IN WHAT'S POSSIBLE IN THE LAB"

theory, there would be no fibre optics, no internet, no smartphones. But physicists have long suspected that another transformation could happen if we become able to build devices that not only benefit from quantum effects, but use them as their main resource.

Examples include quantum teleportation, which relies on a phenomenon called entanglement – where the states of two particles are correlated, regardless of how far apart they are. Researchers have already successfully teleported information over 100 kilometres through optical fibre cables and over 12,900 kilometres via satellite, and the idea is that this ability could underpin a faster, more secure quantum internet.

There is also quantum sensing, which promises orders of magnitude more sensitive measurements of all kinds that could then supercharge navigation, geological exploration and medical diagnostics. But the question remains whether these quantum technologies will ever transcend niche applications. Quantum computers, on the other hand, could have a much wider impact, just as their more traditional predecessors did.

Their potential is a result of the seemingly subtle distinction in the way the two kinds of computers work. In traditional processors, the key role of electrons is to encode information into a series of 1s and 0s, or bits, which can be interpreted as turning electric currents on and off. In a quantum processor, on the other hand, information is encoded into quantum properties of particles or atoms themselves – they are not stage hands that orchestrate computations, but rather its lead actors.

This is why quantum computers can handle more information at once than their classical counterparts. Quantum bits, or qubits, offer more encoding choices than just 1 or 0. To be clear, a qubit cannot simultaneously encode both, but it can occupy a "superposition" where it is effectively both and neither until it is measured. If this sounds strange, it is – and working out what quantum theory really means for the nature of reality is an ongoing puzzle (see "The meaning of quantumness", page 35). In practice, though, these states make quantum computers very powerful. All numbers between 0 and 1023 can be encoded in just 10 qubits, while a traditional computer would need 1024 traditional bits to do the same.

The promise of quantum computing, then, is that in a scenario where a traditional computer runs out of resources while working on a calculation, a quantum machine would do just fine. Researchers have dreamed of such capabilities since the 1980s, and they have spent decades painstakingly building prototypes.

QUANTUM SUPREMACY

Now, their work seems to be paying off. The best quantum computers in existence today – some of which boast 1000 qubits, compared with the 50 we could muster a few years ago – can solve a select few proof-of-principle problems that would indeed be impossible for even the world's best supercomputers, a feat of what researchers call "quantum supremacy".

"In the last five years, there really have been pretty remarkable advances in what's possible in the lab," says David DiVincenzo at Forschungszentrum Jülich, a national research institution in Germany. "The bar keeps going up." Almost 20 years ago, he proposed seven conditions for constructing a working quantum computer, now known as DiVincenzo criteria, and hundreds of researchers are racing to check them all off.

The pace of progress has been startling. "I'm surprised that in 2025 we've reached this point [of advancement]," says Brian DeMarco at the University of Illinois Urbana-Champaign. But standing in our way is the fact that quantum states are inherently fragile. A qubit left on its own is liable to lose its special properties when exposed to even the tiniest disturbance in its environment. This means quantum computers tend to accumulate lots of small errors as they perform calculations, rendering their outputs unreliable. So, the race to build a useful quantum computer is, to a great extent, the race to build one that is "fault-tolerant". Scaling up the number of qubits involved will be important too, because the computational power of a quantum computer increases with the number of reliable qubits.

The good news is that several different ways of making qubits – from assembling them out of superconducting circuits to using cold atoms controlled by lasers – have made a big difference to how well we can stabilise them. "There have been a lot of really creative developments," says DeMarco.

More will surely be needed. When he imagines a million-qubit device, DiVincenzo says he envisages whole rooms filled with machinery, not unlike those in particle-collider facilities like the Large Hadron Collider at ›

CERN in Switzerland. A quantum computer comprising a million superconducting qubits would have to be housed in a massive fridge because those qubits only work at incredibly low temperatures, and its control system would require thousands of wires. Similarly, scaling up a quantum computer made from extremely cold atoms could require thousands of lasers. One solution may be to connect many smaller quantum computers into one machine instead.

But what may really hold us back from truly transformative applications – and what often gets overlooked in coverage of fault-tolerant quantum computers – is that we don't know what sorts of problems these devices will be best suited to tackle. That's difficult to divine because the details of the quantum laws that govern qubits make it hard to take full advantage of a quantum computer's seemingly gargantuan computational power. Superposition states, where a qubit is neither encoding just 1 nor just 0 at once, invites the mental image of the quantum computer running calculations with both values in parallel. The reality is much more subtle and practically challenging, says Māris Ozols at the University of Amsterdam in the Netherlands.

What really sets apart a qubit in a superposition from a classical bit is that it is possible to tell whether a bit is encoding 1 or 0 with 100 per cent probability. Whereas for the qubit, it may only be possible to say that upon measuring it, you will find 1, say, 30 per cent of the time. Calculations on quantum computers are sequences of changes to their qubits' states. If those states are superpositions, and if they are correlated with each other, that can benefit the computation. But to read out what the quantum computer did, you have to measure those states. The measurement will produce different answers with different probabilities, but never all of them at once.

This means there are problems for which the quantum approach doesn't guarantee a faster path to a solution. In determining whether a random string of 0s and 1s has an odd or even number of 1s, for instance, a classical and a quantum computer would both take the same amount of time. Choosing the correct problem, and the correct algorithm for implementing it, is crucial for making the most of quantum computers' potential. It also happens to be very difficult.

Mathematical disciplines such as complexity theory may offer some hints about what sort of problems may be solved on quantum computers with the most significant speed-ups compared with the classical approach. But the truly great quantum algorithms "are sort of rare jewels that one stumbles upon from time to time", says Ozols. "There is no simple, unified method for building quantum algorithms. It's more of an art."

Until we have bigger quantum computers that make fewer errors, we are in something of a catch-22 situation. "We cannot run cutting-edge quantum algorithms yet, so development is happening in this kind of theory world where you're developing algorithms and proving that they should work, but you are never able to practically check," he says.

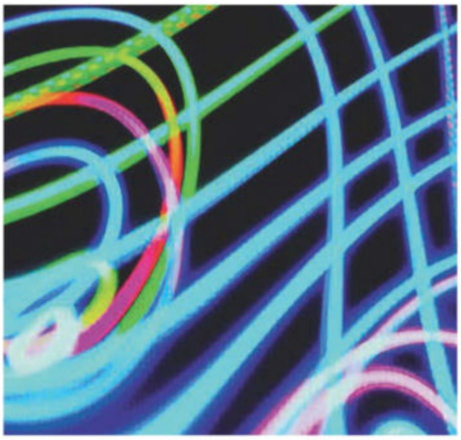
Even the most famous quantum computing algorithm (discovered by mathematician Peter Shor in 1994), which researchers are certain could break encryption keys that no traditional algorithm can, cannot be practically implemented on existing quantum computers because they are too small and error-prone. "We don't have the ability to play around with algorithms on hardware," says Ozols.

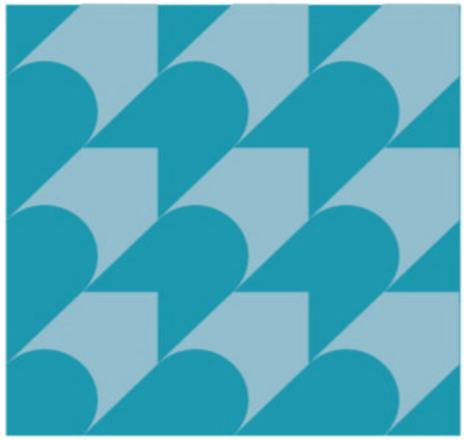
So what applications, and what impact on society, should we expect from quantum computers as they keep advancing? There is a case for optimism. In the past couple of years, several teams have made significant progress towards error-corrected quantum computers. For example, researchers at Google Quantum AI showed they can increase the number of qubits in their Willow quantum computer in such a way that the bigger machine actually makes fewer errors. This is exactly what is necessary to make large fault-tolerant machines. If that momentum continues, within a few years, quantum computers might be able to handle problems in chemistry and materials science with real-

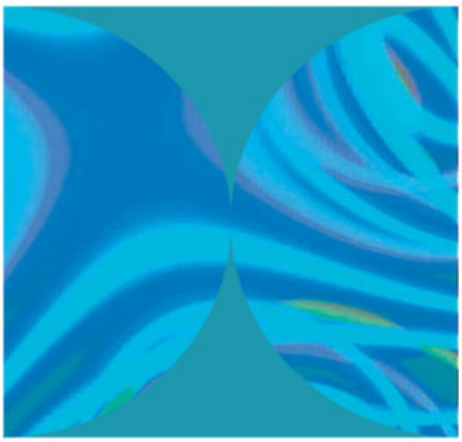
› **1935** **Schrödinger devises a thought experiment in which a cat in a closed box may be considered both alive and dead while it is unobserved. Einstein, Nathan Rosen and Boris Podolsky write a paper on quantum entanglement, which links two particles even when separated by vast distances. They argue that entanglement implies quantum mechanics is incomplete.**

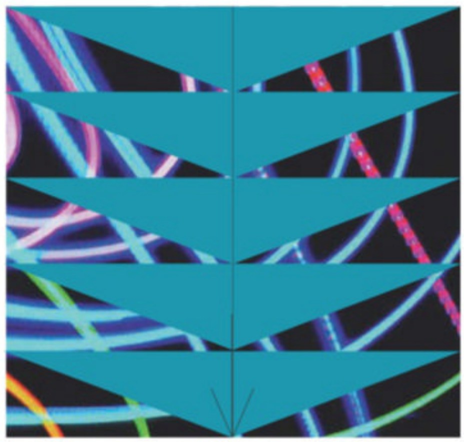
› **1938** **Using ideas from quantum theory, Lise Meitner and Otto Hahn discover nuclear fission, the process that would undergird the development of nuclear power – and nuclear bombs.**

› **1950** **Julian Schwinger, Richard Feynman, Freeman Dyson and Shinichiro Tomonaga develop the modern form of quantum electrodynamics, explaining how light and matter interact. It forms the basis of modern particle physics.** ›









UNSPLASH

world applications, especially if used as part of a larger computing ecosystem, says DeMarco.

They could find use in figuring out the properties of molecules that could upgrade the catalysts in fuel cells or that may become an ingredient for the next generation of solar panels. In the field of materials science, they could help model and create better superconductors that transmit electricity losslessly, without having to be cooled.

Quantum computers could also boost drug discovery. In fact, they are already being used for calculations that help identify the best ways for drugs to bind to biological molecules and to predict which potential drug molecules may ultimately prove to be toxic. More ambitiously still, some researchers even want to run artificial intelligence programs on quantum computing hardware. Such programs aren't a natural fit for quantum computers in the way that, say, chemistry is, and there is no consensus on how practical the proposal may be.

While those kind of advances may be a long way off, quantum computers are already making some progress. John Preskill at the California Institute of Technology in Pasadena says there have already been dozens of discoveries filling gaps in how we understand the inner workings of our world – what he calls "discoverinos". These include insights into how chains of atoms develop magnetism, simulations of exotic "time crystals" that seem to stay in motion forever and studies of systems that can selectively resist the universe's march towards increased disorder, or entropy.

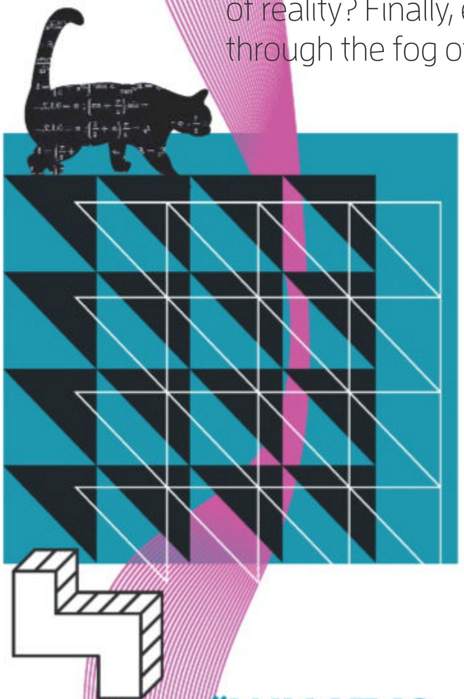
For Aziza Suleymanzade at the University of California, Berkeley, quantum computing is worth pursuing regardless of what applications we can find in the near term. She points to the example of the Laser Interferometer Gravitational-Wave Observatory, which detects ripples in space-time made by cataclysmic events like black hole collisions. Adapting quantum methods for controlling light, not unlike those used in some quantum computer designs, led to a large increase in the frequency of these detections. The continued push to master quantum effects so comprehensively that we can build a million-qubit quantum computer is bound to have similar secondary effects, she says.

Ultimately, DeMarco says the uncertainty about which kinds of algorithms will work best on quantum computers makes it difficult to predict what impact they will have. Which isn't to say they won't change the world – more that we just aren't quite certain how yet. DeMarco compares the question to asking someone who was building personal computers in the 1970s to predict the existence of the iPhone. "I'm actually the most excited about the things that we can't foresee," he says.

Karmela Padavic-Callaghan is a physics reporter at *New Scientist*

THE MEANING OF QUANTUMNESS

What is quantum theory telling us about the nature of reality? Finally, experiments may be able to cut through the fog of confusion, says **Daniel Cossins**



THE problem with quantum mechanics, or at least the reason even physicists don't understand it, isn't that it paints an unfamiliar picture of reality. It isn't difficult to accept that the world of fundamental particles, of which we have no direct experience, is radically different to the world we perceive.

The problem is instead that it doesn't portray the hinterlands between these two worlds, offering no clear outline of how one emerges from the other. As a result, a century after it was committed to canvas, we still don't know what this scientific masterpiece means for our understanding of reality.

We aren't short of ideas. Which of them you prefer is largely a matter of taste, or at least philosophical consideration, because they don't tend to submit to experimental testing. As physicist N. David Mermin has joked: "New interpretations appear every year. None ever disappear."

> "WHAT IS GOING ON BEFORE A MEASUREMENT? QUANTUM THEORY SIMPLY DOESN'T SAY"

NO SUCH THING AS REAL?

In the past decade, however, something has begun to shift. One new twist on quantum theory is the first to make explicit observational predictions, raising hopes of empirical progress. Another, meanwhile, has gathered momentum because it can seemingly solve several perplexing quantum mysteries in one fell swoop – even if it implies that there is no such thing as objective reality after all.

More promising still, physicists have even begun to feel out new ways to test the validity of such assumptions. As they turn mind-boggling thought experiments into real-world tests, we might finally be able to make progress on the question of what quantum theory is trying to tell us. "We can now narrow down the possibilities," says Eric Cavalcanti, a quantum physicist at Griffith University in Queensland, Australia.

The development of quantum mechanics in the mid-1920s upended long-held intuitions about how the universe works (see "Quantum theory's unsung hero", page 29). Ever since Isaac Newton formulated his laws of motion and gravitation in the 17th century, › physicists had built theories in a particular way: you have a physical system and equations that tell you how it will change over time.

But classical mechanics cannot describe the behaviour of subatomic particles like electrons and photons. Experiments show that these particles perform bizarre feats – sometimes behaving like waves, say – and appear to exist in a "superposition" of many possible states at once. Only when you measure them do they take on definite properties.

The Schrödinger equation captures this vagueness, incorporating a mathematical concept known as the wave function to encode all possible observable outcomes. That allows us to calculate the probability that our particle will manifest in a particular place upon measurement, at which point the wave function is said to "collapse". But it can't tell us for certain the outcome of a single measurement. In other words, all we have, until we look, are probabilities.

EXALTED UNKNOWNS

What is going on before a measurement? Quantum theory doesn't say. Nor does it specify what counts as a measurement. It doesn't even tell us whether the wave function, often referred to as the "quantum state", really represents physical reality. For such an exalted theory, that is a lot of unknowns. But, ultimately, they all boil down to one profound question: how does the predictable world we see, which is itself ultimately made of atoms and particles, emerge from this ethereal quantum netherworld? Physicists call this the measurement problem, and it remains the central mystery of quantum mechanics.

The textbook answer is the Copenhagen interpretation, named after the Danish city where it took shape. It holds that we can say nothing about a particle's state before it is measured. The maths works, so "shut up and calculate", in another of Mermin's' memorable phrases. But Copenhagen was controversial from the start, with Albert Einstein famously railing against the apparently probabilistic nature of the quantum world with his insistence that God does not play dice with the universe.

Many physicists still feel Copenhagen is a cop-out. "It's not a serious answer to the question of what is there, in reality," says Roderich Tumulka, a theoretical physicist at the University of Tübingen in Germany. "We want statements about the true nature of reality." It also seems to leave open the seemingly absurd idea that it is us humans, the conscious beings making the observations, who collapse the wave function.

Tumulka is among those who prefer interpretations that treat the wave function as physically real – something that represents the world as it exists whether we are looking or not. The most famous is the many-worlds interpretation, the idea that all possible outcomes contained in the wave function are realised upon measurement in many separate universes branching off from ours.

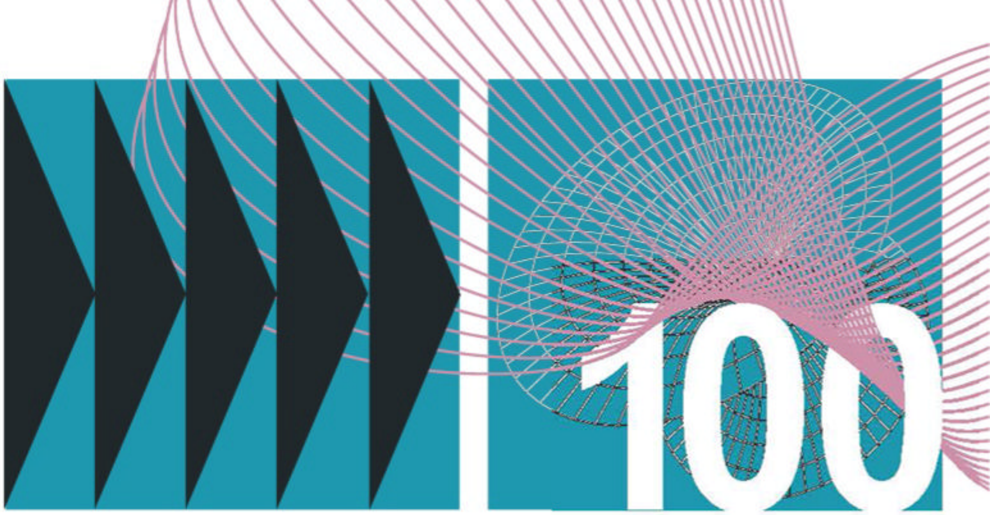
But there is also objective collapse, a suite of models proposing that quantum mechanics is incomplete and that something else has to be tacked onto the Schrödinger equation to explain wave function collapse. "The [key] difference with the standard interpretation is that the collapse of the wave function is not something that occurs by magic at the end of the measurement process," says Angelo Bassi, a theorist at the University of Trieste in Italy. "It's just part of the dynamics."

Collapse models have garnered more attention than most in recent years, partly because they offer a plausible explanation of how classical reality emerges without reference to human observers. We don't see large objects like picture frames and paint brushes in a superposition, it says, because the collapse process works in such a way that the more interacting particles there are, the more readily collapse occurs.

What triggers this continuous collapsing isn't entirely clear. Some models don't say, others posit that it is just gravity. But Bassi says there may ultimately be no good answer – it may just be a property of nature. "That's why I like collapse models, because they try to open the door to a new world which we don't understand at the moment – something beyond quantum mechanics that we are not grasping."

What really sets collapse models apart, however, is that they can be put to the test. Uniquely, they make explicit observational predictions that differ from what standard quantum mechanics predicts. The idea is that this constant process of spontaneous collapse should cause quantum objects such as particles to constantly jiggle around, which, in turn, means they emit excess energy that should be detectable, even if the signal is extremely faint.

For the past decade, Bassi has been working with colleagues around the world on an ambitious experimental programme in search of such a signal. They have mostly been



› **1957** **Hugh Everett introduces an idea that later becomes known as the many-worlds interpretation. It suggests that all possible outcomes of a quantum process are real across multiple parallel universes.**

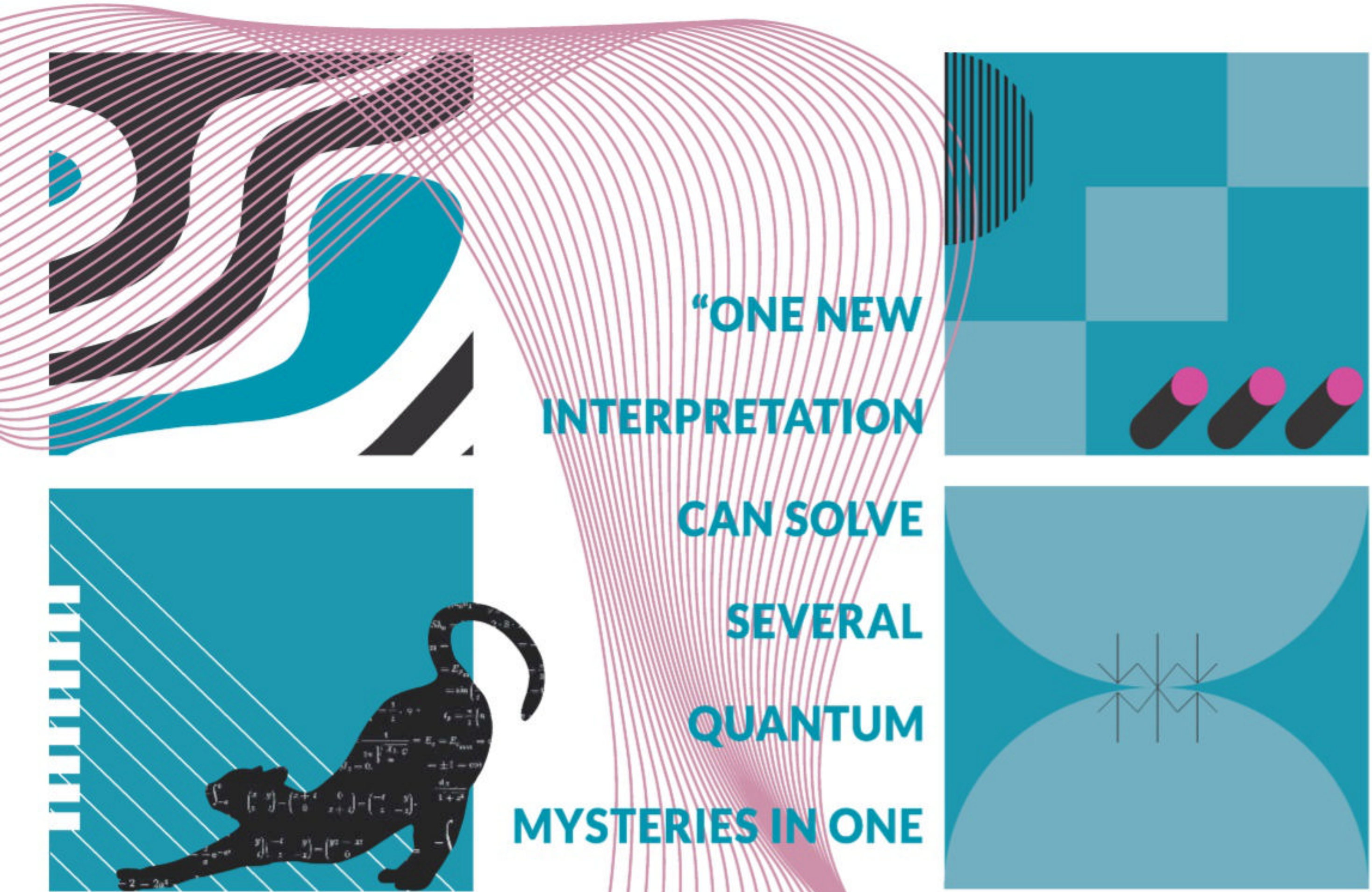
› **1961** **Eugene Wigner proposes a more involved version of the 1935 thought experiment Schrödinger's cat. Known as Wigner's friend, it shows up the weirdness of quantum theory in new ways.**

› **1964** **John Stewart Bell produces an expression that defines whether the behaviour of entangled particles can be explained by the "hidden variables" Einstein wanted. His own and later experiments show they can't, and quantum theory really is as strange as it seems.**

› **1994** **Carlo Rovelli and Lee Smolin publish a founding paper on loop quantum gravity, one of several frameworks that attempt to describe space-time itself as quantised – or made of infinitesimally tiny "grains".**

› **1998** **The first experimental quantum computer is reported – it has just two quantum bits.**

› **2016** **China launches the Micius satellite, designed to distribute quantum encryption keys and so enable long-distance communication that is, in principle, unhackable.** ›



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> **"ONE NEW INTERPRETATION CAN SOLVE SEVERAL QUANTUM MYSTERIES IN ONE FELL SWOOP"**

repurposing detectors designed to sense hints of dark matter or elusive particles called neutrinos, such as the ultra-sensitive instruments located deep underground beneath the Gran Sasso massif in Italy. And the results are trickling in. In 2020, for instance, a team including Bassi and Cătălina Curceanu, an experimentalist at Italy's National Institute of Nuclear Physics, was able to rule out the simplest form of one model in which gravity does the collapsing.

Similar experiments are ongoing, and with each new analysis we get fresh constraints on which, if any, of these models might work. But while the fact that we finally have a shot at ruling out objective collapse with experimentation is itself progress, actually doing so is a slow process. "So far, we saw no signal, but this is just the beginning," says Bassi.

If we were to detect a signal that everyone can agree supports objective collapse, it would surely be worthy of a Nobel prize. Whether that would immediately tell us anything about the meaning of quantum theory is another matter, according to Magdalena Zych at Stockholm University in Sweden, because we would still have to figure out what it is in the environment that is doing the collapsing.

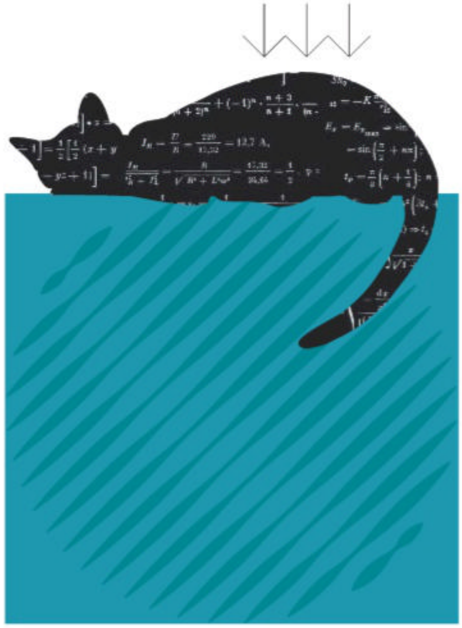
"It would solve the measurement problem in the sense of, if you believe that quantum theory is missing something, this is it," says Zych. "But it doesn't really reveal what quantum mechanics is telling us about reality, because you still have to impose some meaning yourself to some extent: you have to say what is the 'noise' in the environment [that collapses the wave function]."

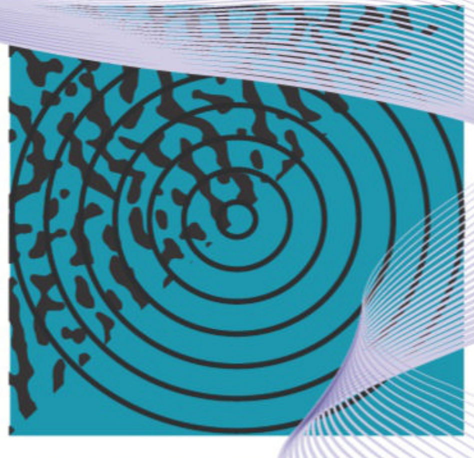
More importantly, Zych says we would also be none the wiser about why the observable properties of quantum objects emerge in a probabilistic way, from the act of measurement itself. "That's really the deep mystery of all this, the fact that we have to speak about probabilities at all," she says. There is no self-evident reason why the behaviour of subatomic particles cannot be governed by deterministic laws. The fact that they aren't demands an explanation.

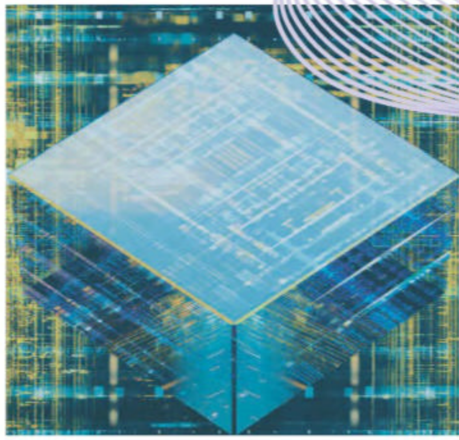
A MINISTER'S VIEW

For Zych, the take on quantum mechanics that tackles that challenge head on falls into a whole different category of interpretations. While the likes of Bassi and Tumulka insist that quantum states are real, some physicists take a starkly different view: that they don't represent independent reality at all.

Arguably the most striking example of this approach is QBism, originally known as Quantum Bayesianism because it is founded on a framework for interpreting probabilities first developed by 18th-century minister Thomas Bayes. ›







› 2019 **Google uses a quantum computer with 53 qubits to claim it has reached "quantum supremacy" – that is, solving a computational problem that no classical computer can feasibly solve. (Advanced non-quantum computers have since pulled off the same feat.)**

› 2023 **Start-up Atom Computing unveils the first quantum computer with more than 1000 qubits.**

Conventionally, probabilities are viewed in "frequentist" terms: we count up the outcomes of many coin tosses to conclude that the odds of getting heads or tails are 50/50. Similarly, many measurements of a particle give you the relative probability of it having one state or another when measured. The Bayesian approach, by contrast, recasts probability as a subjective value that updates as you gain more information.

Running with this idea, the central argument of QBism is that quantum mechanics is similarly subjective. It supplies recommendations about what an observer should believe about what they will see on making a measurement, allowing them to update those beliefs as they take into account fresh experiences. "It's a theory for agents to navigate the world," says Ruediger Schack at Royal Holloway, University of London, who developed QBism with Chris Fuchs at the University of Massachusetts Boston.

The appeal of this interpretation is that it seems to address several quantum conundrums at once. It deals with the measurement problem by providing and even requiring a central role for subjective experience. The mysterious collapse of the wave function is simply the observer updating their beliefs on making a measurement, says Schack.

QBism's answer to the question of how classical reality emerges from the quantum fog, meanwhile, is that it is a result of our actions on the world, of our constant updating of our beliefs about it. The idea even makes light work of a notorious conundrum known as the Wigner's friend paradox, a thought experiment proposed in the 1950s by physicist Eugene Wigner. Essentially, it demonstrates that two observers – Wigner and a friend observing him making measurements on a quantum system – can have two contradictory experiences of reality.

For a QBist, there is no paradox because a measurement outcome is always personal to the person experiencing it. All of which means that QBism stands starkly athwart the idea that it is possible to achieve an objective view on the universe. But that is exactly the point, says Schack, and this is the great lesson of quantum mechanics: that reality is more than any third-person perspective can capture. "It's a radically different way of looking at the world."

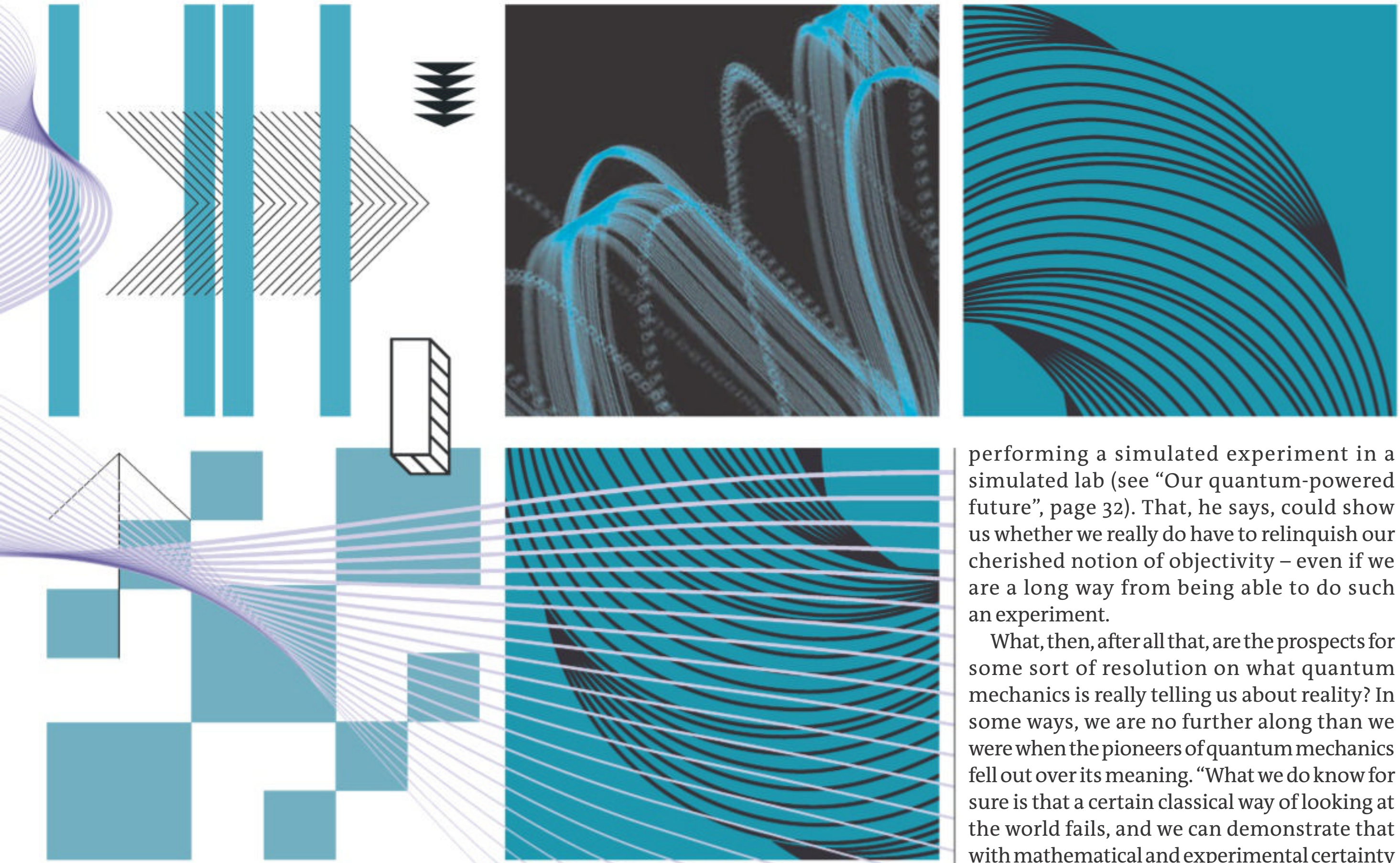
Others find QBism hard to swallow. Bassi, for instance, insists that objective reality is too high a price to pay. "What physics is about is describing nature in an objective way," he says. Another problem is that QBism doesn't appear to offer any observable predictions differing from standard quantum mechanics, and no realistic prospect of submitting to experimental tests. "Convincing people might be a case of pointing out the inadequacies of the alternatives," says Schack.

That arguably leaves us back where we started. If our best hope of an empirical solution to the measurement problem would leave open questions even if it were proved correct, and an alternative that can address those questions can't be tested, where do we go from here?

There might still be cause for optimism. In the past few years, some physicists have begun to demonstrate that the assumptions underpinning how we think about the meaning of quantum theory – typically considered more in the realm of metaphysics than science – might themselves submit to testing.

They call it experimental metaphysics. "It's an approach that tries to be clear about the landscape of metaphysical assumptions made by different interpretations," says Cavalcanti, who is one of its key proponents. Among those assumptions are the absoluteness of observed events, which is to say that the outcomes of a measurement are the same for all observers; freedom of choice, the notion that the outcome of any measurement isn't due to factors involved in the measurement; and locality, or the idea that a free choice cannot influence the observed outcome of an experiment at a distance or in the past. "Individually, these may not be testable, but when you group them together, they can be," says Cavalcanti. In this way, you can potentially at least disprove classes of quantum interpretation, he says.

Cavalcanti was part of the team behind the most powerful demonstration of this approach to date. In 2020, he and his colleagues used photons to perform an extended version of the Wigner's friend thought experiment that also involved entanglement, another quantum phenomenon that links particles across vast distances. In short, they found that if standard quantum mechanics is right – if we find no signals for objective collapse, for example – we must abandon one of these assumptions: locality, freedom of choice or the absoluteness of observed events.



That placed the most stringent constraints yet on physical reality, says Cavalcanti. "If you want to keep the notion of freedom of choice, together with locality, then you need to reject the assumption of absoluteness of observed events," says Cavalcanti – just as QBism insists we must. So, although we aren't at a stage where we can say QBism or any other interpretation is the right way to think about the meaning of quantum mechanics, "we can now narrow down the possibilities," says Cavalcanti.

FRAGILE STATES

He now wants to go further. In their 2020 experiment, Cavalcanti and his colleagues used photon detectors in place of Wigner and photons themselves as a proxy for his friend. Yet photons are obviously a far cry from the human observers imagined by Wigner in the 50s, and most people would presumably say photons don't count as observers. It is extremely difficult to keep a molecule comprising a couple of thousand atoms in a superposition, owing to the fragility of quantum states, never mind anything approaching the complexity of a human. But Cavalcanti and his colleagues have suggested that we might one day do the same experiment with an advanced artificial intelligence algorithm running on a large quantum computer, performing a simulated experiment in a simulated lab (see "Our quantum-powered future", page 32). That, he says, could show us whether we really do have to relinquish our cherished notion of objectivity – even if we are a long way from being able to do such an experiment.

"WHAT REALLY SET COLLAPSE MODELS APART IS THAT THEY CAN BE PUT TO THE TEST"

What, then, after all that, are the prospects for some sort of resolution on what quantum mechanics is really telling us about reality? In some ways, we are no further along than we were when the pioneers of quantum mechanics fell out over its meaning. "What we do know for sure is that a certain classical way of looking at the world fails, and we can demonstrate that with mathematical and experimental certainty as much as we can know anything in science," says Cavalcanti.

For now, we have to each decide for ourselves which of the various interpretations of what quantum mechanics means is more appealing based on theoretical considerations – whether you are prepared to give up one assumption or another, and what price you are happy to pay in turn for keeping the assumptions you prize above all else.

Cavalcanti says we would ideally get some guidance from our attempts to figure out if quantum mechanics fits with Einstein's general theory of relativity, which describes gravity as the result of mass warping space-time. If a particular interpretation helps us make progress on that front, he says, it would be a strong clue. "I think these foundational experiments are relevant here," he says. "Because the question of whether or not events are absolute is important for the construction of a viable theory of quantum gravity."

In the meantime, we have at least begun to clarify things by putting the problems quantum mechanics throws up in terms we can understand and devising experiments that can narrow down the plausible solutions. And all we can do is to strive for ever more sophisticated ways to do that, says Cavalcanti. "I think you can't understand the world less by understanding more than one way to see it." ∎

Daniel Cossins is a writer based in London

ALAMY

Raising the bar

With the cost of cocoa soaring in response to high demand and the impact of global warming on crop yields, **Michael Le Page** finds that the race is on to master lab-grown chocolate


CALIFORNIA CULTURED

IT IS by far the rarest and most exclusive chocolate I have ever eaten. In fact, you can't even buy it in shops. It doesn't look that special, though – just a few flattened droplets a slightly lighter shade than most dark chocolate, sealed in a tiny plastic bag.

It smells like dark chocolate and tastes like it, too, but better – less bitter. Most of all, for me, there is no doubt that this is the real thing.

That is important because what I am eating wasn't made using cocoa beans sourced from trees like normal chocolate. Rather, it was grown in a glass flask by California Cultured, one of several firms aiming to mass-produce chocolate in vats using cell culture technology.

Cultured chocolate could be even better than the tree-grown kind, claims Alan Perlstein, CEO of the company, with higher levels of chemicals such as polyphenols that might have health benefits, no contaminants such as heavy metals taken up from the soil or pesticides sprayed on crops, and a taste that rivals anything on the market now. "We're trying to create flavours that are almost unobtainable through traditional chocolate manufacturing," he says.

For many chocolate companies, however, the main appeal of getting raw ingredients from vats instead of trees is the potentially unlimited supply. Climate change is hitting cacao farms hard, leading to shortages – the price of cocoa beans has quadrupled after remaining relatively stable for decades.

So, can chocolate grown in a vat really compete with the tree-grown variety on price? And will consumers embrace it?

Melting in the heat

Cocoa beans, the raw material that becomes chocolate, are the seeds of the cacao tree, native to South America but now grown more widely in tropical regions around the equator. The fruits, called pods, that contain the beans are harvested by hand, chopped from the tree with a knife and split open to reveal the wet beans inside. The beans are fermented, roasted and ground up, then separated into cocoa butter, which provides the melt-in-the-mouth texture of finished chocolate, and cocoa solids, which give the flavour. Dark chocolate is made by combining cocoa solids with cocoa butter and usually some sweeteners. Milk chocolate contains milk powder or condensed milk as well, while white chocolate is made using cocoa butter with no cocoa solids.

But while demand for chocolate is rising, in recent years, supply has been falling. "Every chocolate company is desperate," says Perlstein.

Global warming is making it harder to grow cacao trees: rising temperatures are rendering conditions too hot and rainfall is more erratic, while trees weakened by extreme weather are more vulnerable to pests and disease.

"Climate change will definitely affect the yields," says Thomas Wanger at Westlake University in Hangzhou, China, whose team has shown that higher temperatures have just this effect.

More than half of all cocoa beans come from West Africa, so any extreme weather or disease outbreak there has a big effect on global supply. In January 2025, for example, a particularly dry Harmattan wind blowing in from the Sahara caused pods to wither on the trees and cocoa prices to soar. Chronic problems, such as illegal gold mining, which pollutes soil and water resources, are also affecting many farms in that area.

The cultured approach

Lab-grown chocolate could remove the unpredictability of relying on tree-grown chocolate. "Years ago, we started to think, OK, climate change is affecting the yield and the quality of the cocoa," says Heli Anttila at Fazer, a Finnish chocolate company that has been working on lab-grown cocoa. "We need to have alternatives. Cocoa is an important raw material."

Working with selected cacao varieties, cultured-chocolate makers take a small number of cells that would normally form the cocoa beans. They place the cells in a liquid medium containing nutrients and plant hormones, which can be extracted from other foods such as rice and coconut milk. In the lab, the cells are grown in glass flasks, with the liquid turning dark brown as the cells divide and mature. The resulting material, ready in about a week, is fermented and roasted. For commercial production, the cells would be grown in large, stainless steel vats. It doesn't matter that the texture of the brown paste that is produced is different to that of tree-grown beans, as both are very finely ground to produce chocolate.

Tilo Hühn at the Zurich University of Applied Sciences in Switzerland says the chemical composition of cultured cocoa bean cells is very similar to that of tree-grown beans. "In our cell cultures, we find comparable concentrations, in some cases higher concentrations, of polyphenols and aroma components," says Hühn, who started trying to culture chocolate more than a decade ago. "This is really close to production on trees. It's not the same, but it's close to it."


USAID/ALAMY

Above: cacao harvesting is done by hand, usually on small farms; opposite: lab-grown chocolate from California Cultured

Creating cocoa in a lab can also be done as needed, rather than waiting on seasonal harvests or the three to five years it takes for newly planted cacao trees to start fruiting. Cell-culture products should be more consistent because every aspect of the process can be controlled.

At the moment, the level of cocoa butter, which normally makes up half of the raw product obtained from the pods of the cacao tree, is lower in lab-grown cocoa than is ideal. The sample I tried contained added tree-grown cocoa butter to smooth out the texture, but Perlstein says California Cultured has got cocoa butter percentage levels to "double figures" by tweaking conditions to keep cells in the cocoa butter-producing stage for longer. The company aims to increase that figure further. Another option would be to add other vegetable fats to the mix to make chocolate, as is routine in countries such as the UK.

The biggest challenge now is ramping up production to an industrial scale, at a cost comparable to that of tree-grown chocolate. What is clear is this is much more feasible with cultured chocolate than with one of the other lab-grown foods making headlines, cultured meat. For that, the growth medium can cost upwards of $20 a litre and the cells often die en masse, says Hühn. With a 50,000-litre vat, say, that is a massive loss. But plant cells are much less prone to dying and the growth medium is far cheaper. Perlstein says California Cultured has got the cost of the growth medium below $1 per litre and is aiming to get it down to 2 cents.

Achieving price parity with conventional chocolate also got a lot easier when cocoa prices hit an all-time high in December 2024 – around $12,000 a tonne, up from around $3000 a tonne in 2023. "It was insane," says

> "We're trying to create flavours that are almost unattainable through traditional methods"

Hühn. "This makes the cocoa field, let's say, more interesting." Perlstein thinks prices of farmed cocoa could quadruple again.

Assuming mass production is feasible, it is likely to be at least a year before cultured chocolate is sold commercially in the US, longer in Europe. As a new kind of food, it will require regulatory approval, and it isn't clear whether it will legally be able to call itself chocolate.

If and when when it does hit shelves, should we buy it? Farming chocolate is, like nearly every crop, bad for the environment. In most places, cacao trees are grown as a monoculture on deforested land, so meeting rising demand with cultured chocolate rather than more farms of this sort could prevent further deforestation. Ethically, too, some cacao farming has a reputation for using forced labour, sometimes provided by trafficked children; cultured chocolate requires very little labour at all.

However, though lab-grown chocolate could alleviate some concerns, it might introduce others. Making the growth medium requires growing more of other crops, and though the approach might have environmental benefits overall, says Wanger, detailed studies will have to be done to confirm this. And then there is the impact on the more than 5 million small farmers across the world who produce cocoa beans. "It would definitely be bad news for farmers," says Bart Van Besien, cocoa supply chain expert at Oxfam Belgium. "Millions of families depend on income from cocoa."

At the moment, however, global demand is growing so fast that it seems unlikely that cultured chocolate will put farmers out of business. "There is a huge difference now between supply and demand," says Tal Govrin at Israel-based cultured chocolate start-up Kokomodo. "We see ourselves as filling the gap."

Ultimately, of course, the success of cultured chocolate will come down to whether consumers buy it. Having tried it, I know I, for one, would. ∎

Michael Le Page is a news reporter at *New Scientist*


New Scientist Live

Puzzles
Try our crossword, quick quiz and logic puzzle p45

***Almost* the last word**
Why do so many animals have white bellies? p46

Tom Gauld for *New Scientist*
A cartoonist's take on the world p47

Feedback
Going viral online isn't what it used to be p48

Twisteddoodles for *New Scientist*
Picturing the lighter side of life p48

Mathematics of life

Plotting it out

A versatile piece of maths can help you solve all kinds of problems, from timetable scheduling to colouring in, says **Katie Steckles**

Katie Steckles is a mathematician, lecturer, YouTuber and author based in Manchester, UK. She is also adviser for *New Scientist*'s puzzle column, BrainTwister. Follow her @stecks

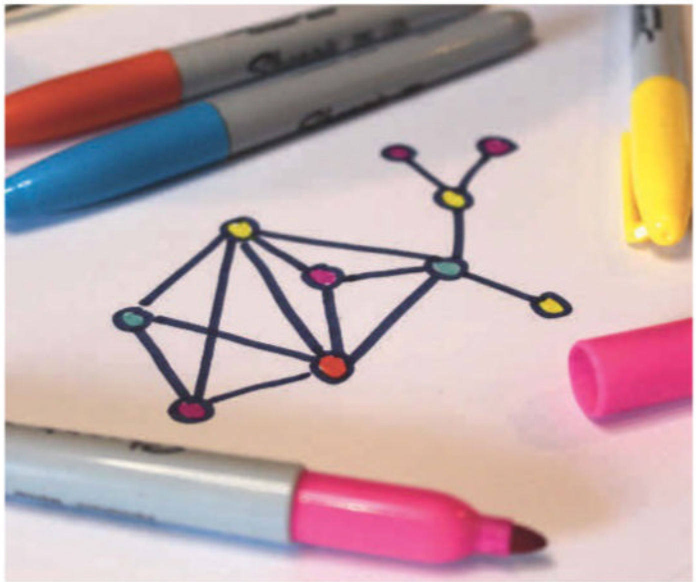
RECENTLY, a friend asked for help with a tricky problem: they were staging a play, and the script had a large number of characters. They didn't want to hire an actor for each role, and while they could double up, they would run into problems if the same actor were playing two characters in a scene.

Luckily, I was the right person to come to for help. There's a piece of maths that's effective at solving many such problems, from casting a play to timetable scheduling – and even colouring in.

Graphs – networks of points joined by lines; see the image to the right – are extremely effective for modelling sets of objects and the relationships between them, with obvious uses in describing structures like computer networks or roads between cities. Mathematicians are often particularly interested in the properties of graphs because they tell us something more about the underlying structure.

One such property is graph colouring. This involves assigning a colour to each point, so that any two points joined with a line are assigned different colours. Finding the minimum number of colours needed to do this can tell us something useful about the graph's structure. For example, a graph with a triangle of points all joined to a fourth point in the centre will need at least four colours to fill it in.

One application is in problems involving actual colouring: given a picture split into connected regions, is there a way to fill it in



KATIE STECKLES

using only a limited set of colours, so adjacent regions are different hues? The proof of the four colour theorem confirmed that for diagrams drawn on paper, four colours at most will ever be needed. These correspond to graphs that can be drawn on a page without any lines crossing.

Even if a graph can't be drawn without crossings, we can still find the minimum number of colours needed to fill it in, and use this to solve problems.

One of my favourite uses of graph colouring is in scheduling problems: imagine a set of classes, with a shared set of students. We can draw a graph, indicating each class by a point, and join two points if those classes have any students taking both (so they can't happen at the same time).

Then, we find a way to colour the graph using the fewest possible colours. The minimum number of colours will tell us how many timetable slots we will need: each colour represents a set of classes with no overlap in students, so they can all happen simultaneously.

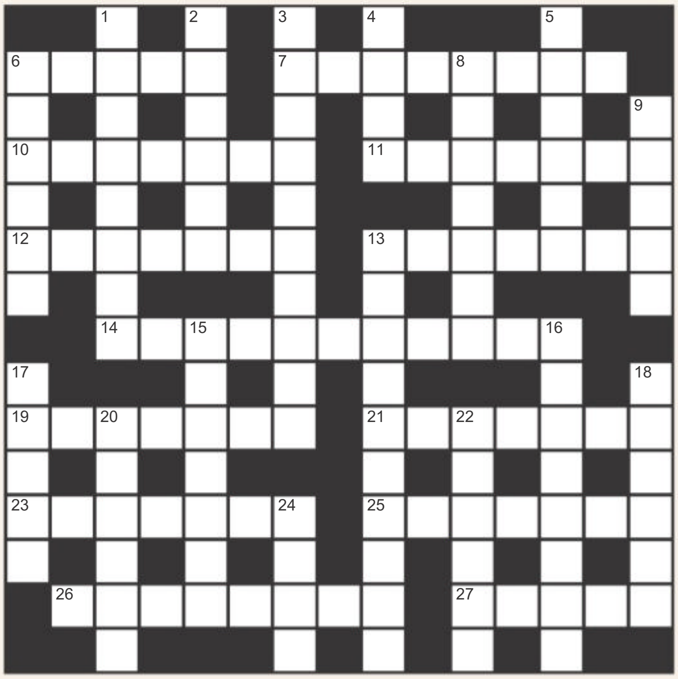
This may tell you how I solved my friend's problem: I suggested they draw a graph, representing each character with a point, and join two characters with a line if they appeared in any scenes together. Colouring this graph minimally then told them exactly how many actors they would need to stage the play. Another victory for maths – on with the show! ▮

Mathematics of life appears monthly

Next week
Debunking gardening myths

These articles are posted each week at newscientist.com/maker

Quick crossword #181 *Set by Richard Smyth*



Scribble zone

Answers and the next cryptic crossword next week

ACROSS

6 Major blood vessel (5)
7 Parts of the auricles (8)
10/11 Exploratory mission to Saturn launched in 1997 (7-7)
12 Fixed vertebrosternal bone (4,3)
13 Hydrocarbon, $C_6H_5CH_3$ (7)
14 Upper central part of the abdomen (11)
19 Cheek (7)
21 Robust threaded fastener (7)
23 Area of altered vision (7)
25 Code name for the first detonation of a nuclear weapon (7)
26 First synthetic plastic (8)
27 Abnormal growth from a mucous membrane (5)

DOWN

1 P (8)
2 Charles ___, X-Men founder (6)
3 Agent K and Agent J, for example (3,2,5)
4 Curved structure (4)
5 Ethenone, say (6)
6 Bow-shaped (6)
8 Form of thrombocytopenia affecting some populations in central Africa (7)
9 Tree in the *Populus* genus (5)
13 Moments of complete eclipse (10)
15 Haematite or magnetite, perhaps (4,3)
16 Jawbone (8)
17 Overweight (5)
18 Remain vertical (4,2)
20 Insect body segment (6)
22 Electronic (or avian) noises (6)
24 X, Y or Z, possibly (4)

Our crosswords are now solvable online
newscientist.com/crosswords

Quick quiz #298
set by Corryn Wetzel

1 What did US chemist Roy J. Plunkett accidentally invent in 1938?

2 What is the dispersal of seeds by animals called?

3 Which element's name comes from the Greek word for stranger?

4 What does the ACE in ACE inhibitors stand for?

5 What is the largest landlocked country in the world?

Answers on page 47

BrainTwister
set by Katie Steckles and Peter Rowlett

#69 Backward drops

Imagine a number sequence, created from the normal sequence of whole numbers, where each term is that number written backwards, e.g. the 12th term is 21 (and any leading zeroes are ignored). This goes 1, 2, 3, 4, 5, 6, 7, 8, 9, 1, 11, 21, 31, 41, and so on. Each of these numbers is bigger than the last, except that after 9 we get a drop to the next number, which is 1.

When is the next drop?

What is the largest drop in the first 100 terms of the sequence?

What are all the different drop sizes in the first 1000 terms of the sequence?

Solution next week

Patchy puzzle

Why do many animals, such as mammals and birds, have white underbellies?

Herman D'Hondt
Sydney, Australia
Being lighter at the bottom than at the top is called "countershading", and the main reason for it is camouflage. It is regularly found in animals like fish, which are often viewed from below by predators. However, though light usually comes from the sun above, it also works if the animal is viewed from the side. Since the top of the animal gets more light than the bottom, countershading makes overall tone more even and the animal blends in. In such cases, if the bottom were the same dark shade as the top, it would be easier to see against the background.

While a white belly may stand out when standing up, such as with a penguin, for the most part, animals are positioned belly-down, so it rarely has that effect. Countershading doesn't require a fully white belly – a lighter-coloured shade is often sufficient.

There are also cases of reverse countershading to make an animal distinctly visible (dark bottoms and light tops), usually to act as a warning to predators in species with strong defences, such as the skunk. There are some cases of reverse countershading that is still camouflaging, for example in the Nile catfish, which tends to swim and live upside down.

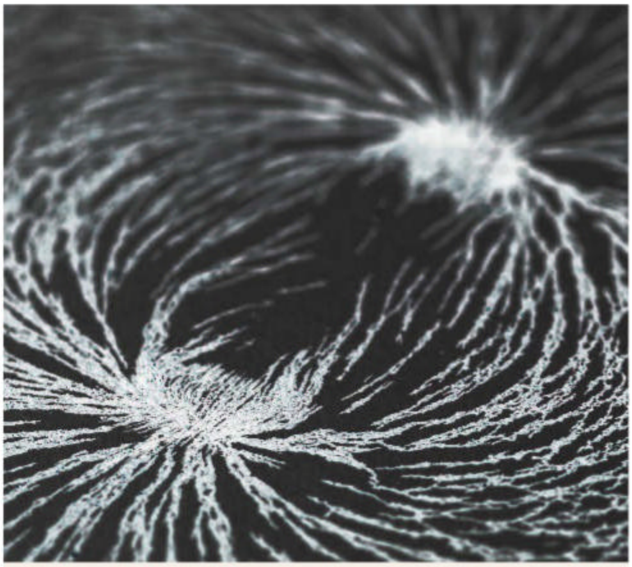
"Countershading is also referred to as 'Thayer's law' after the US artist who was one of the first to study it in the late 19th century"

Countershading is also referred to as "Thayer's law" after the US artist Abbott Thayer, who was one of the first to study it in the late 19th century. In 1902, Thayer was even awarded a patent to paint warships with countershading to make them less visible to the enemy. The US Navy rejected the idea at the time, but in the second world war, many fighter planes used countershading to make them less visible from below.

David Muir
Edinburgh, UK
Imagine that you are a raptor flying over your hunting ground. Two prey animals are below, both pigmented to match the terrain. But one is brown all over, whereas the other is brown-backed with light flanks and a white underbelly. What does the raptor see, and which prey is more likely to be attacked?

When light falls on a uniformly coloured animal, the upper side appears lighter and the underside darker. The visibly lighter parts are then framed by the seemingly darker ones, making the animal easier to detect. An animal with colour gradation from dark above to lighter underneath doesn't suffer this problem; instead its pattern reduces differences in brightness and colour, making it harder to detect. Therefore, the white-bellied prey is more likely to survive and pass on its genes than the uniformly coloured prey.

Reverse countershading, a dark underside and light back, maximises contrast by enhancing the effect of natural light and is the opposite of camouflage. This is used by animals such as the honey badger to signal to predators that they have potent defences, in other words, that they aren't to be tangled with, so potential attackers better beware.



YON MARSH PHOTOTRIX/ALAMY

This week's new questions

Double negative **If I were able to create two negatively charged black holes, could they repel each other? Or does gravity always win? *Michael Diesso*,** *Princeton, New Jersey, USA*

Dig the dirt **Hominin fossils and artefacts are often found in metres-deep sediment in caves. What caused the mess? Didn't hominins clean? *Allen Reynolds*,** *Greenfield, New Zealand*

Would two negatively charged black holes repel each other?

Last peg standing

I recently bought plastic multi-coloured clothes pegs, which have slowly disintegrated in the sun except for the yellow ones. Why?

Peter Holness
Hertford, Hertfordshire, UK
The phenomenon that destroyed the non-yellow clothes pegs is called "unzipping". Many years ago, a chemistry colleague told me about it. His explanation was that the sun emits high-energy photons capable of breaking chemical bonds. This explains things like sunburn and curtains faded by sunlight.

Most plastics are polymers, which are made from smaller units called monomers that link together through chemical bonds. Polyvinyl chloride (PVC), for example, consists of repeating vinyl chloride subunits. In turn, the subunits consist of carbon, hydrogen and chlorine atoms. Sunlight has been known to unzip PVC by dislodging hydrogen and chlorine atoms, creating hydrochloric acid and causing further erosion of plastic subunits. Unzipping potentially affects other plastics, too. It can be slowed or prevented by introducing certain chemical additives to the material. So, one possible explanation for the survival of the reader's yellow pegs is stabilising additions of this sort.

Another explanation for the disintegrating pegs involves both light absorption and heat. The colour of the plastic affects the amount of light reflected or absorbed, and hence heat, with darker colours absorbing more than lighter shades, such as yellow. But without chemical and spectroscopic analysis, it is impossible to know whether the reader's yellow pegs were protected by their colour or additives, or perhaps a combination of both.

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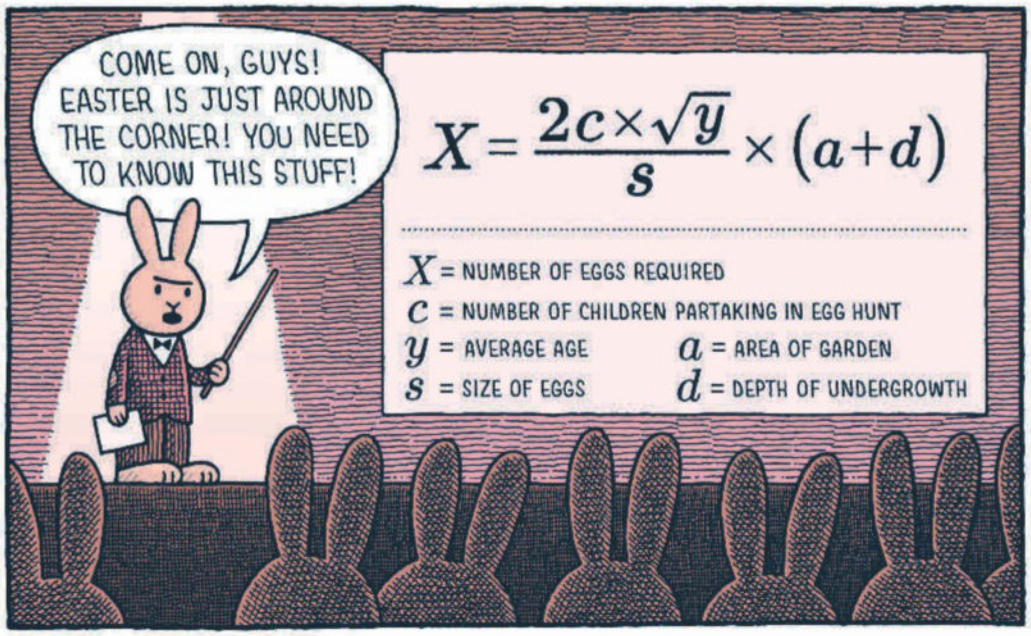
Tom Gauld
for New Scientist



Thirsty work

Is it more efficient for me to carry water in a bottle or in my stomach? (Continued)

Mark Dirnhuber
Bristol, UK
If this purely depended on biomechanics, then the stomach would be more efficient because the load is nearer to the body's weight-bearing axis. But the stomach is seriously leaky: a drink of a few hundred millilitres of water will be absorbed into the body within an hour, some directly from the stomach but most from the small intestine.

The absorbed water lowers plasma osmolality (a measure of the concentration of dissolved particles in the blood plasma – the liquid part of blood) and suppresses anti-diuretic hormone secretion, so the kidneys will excrete most of that excess water within 4 hours. So carry your water in a plastic bottle, lest you end up needing to recycle the lost water from your stomach.

"The stomach is seriously leaky: a few hundred millilitres of water in it gets absorbed into the body within an hour"

Gary Trethewey
Leigh Creek, South Australia
First, look at the notion of efficiency. This refers to reducing the use of one resource – water – at the expense of another resource – effort. For example, a car's fuel efficiency might be improved by changing its size, weight or shape, but this can come at the cost of speed or comfort. Conversely, fast speeds can be achieved by burning more fuel.

So, where to carry water? Our bodies are very sensitive to water balance, so we need to have the right amount within ourselves. Any notion of saving water by storing it in our backpack and going thirsty is dangerous. On the other hand, because of that same sensitivity, any over-hydration simply makes us pee, wasting what we carried on our back yesterday. So, the most efficient way to carry water is to have the right amount in our body and bring the rest in the backpack.

Pat French
Longdon-upon-Tern, Shropshire, UK
Water leaves your stomach in about 15 to 20 minutes. Therefore, if your journey is short and you are likely to find water available on arrival, there is little need to carry it under normal conditions. Harsher conditions, such as high heat or humidity, will raise the rate at which this stomach reserve will be depleted.

Beyond your stomach, water may be considered "involved in the vital process" rather than being stored, and it will need to be replaced with water from your stomach reservoir as the process continues. If you have only a little water, you may as well drink it as carry it. It will be better for your body to use it before becoming affected by thirst than trying to remedy those effects afterwards. ▮

Answers

Quick quiz #298 *Answers*

1 Teflon

2 Zoochory

3 Xenon

4 Angiotensin-converting enzyme

5 Kazakhstan

Cryptic crossword #159 *Answers*

ACROSS 1 Paperbacks, **8** Virgo, **9** Fluvial, **10** Newt, **11** Stallion, **13** Intuit, **15** Weight, **16** Tangents, **18** Char, **21** Reapply, **22** Alpha, **23** Mandelbrot

DOWN 2 Arrow, **3** Enol, **4** Befit, **5** Crueller, **6** Spiking, **7** Planetaria, **8** Vansittart, **12** Finespun, **14** Tone arm, **17** Thyme, **19** Hippo, **20** Barb

#68 Another 2025 puzzle *Solution*

1936 is 44^2, and the divisors of 44 (apart from 44 itself) are 1, 2, 4, 11 and 22. The product of these numbers is indeed 1936.

This only works with square roots that have six divisors: 1, the number itself (which we are excluding), and four others. The factors other than 1 can be paired up so that each pair multiplies to give the number itself (e.g. $45 = 5 \times 9 = 3 \times 15$), so if there are four such factors and we multiply them all together, we will get the square of the original number. 144 is the smallest square with this property.

More viral than viral

If there's one thing Feedback reliably enjoys, it's a neologism: that is, a newly coined word or phrase. The past five years alone have seen the emergence of "bed rotting" (something Feedback would like to do more of), "doomscrolling" (something Feedback does rather too much of) and "sanewashing" (something that is approximately the opposite of what we do here). But how to describe the act of coining a new word? Feedback decided to invent the verb "to neologise", but then we discovered that somebody else had already invented it sometime around 1813.

Congratulations, then, to journalist Taylor Lorenz for neologising "viralflation". Essentially, it means that the bar for something to be considered to have "gone viral" online has gone up so far that it is almost unattainable, and also increasingly meaningless.

As Lorenz explains: "The volume of content being churned out every day has skyrocketed, the life cycle of each piece of media has grown shorter and social media platforms continue to inflate public metrics, devaluing previously impressive online stats."

Because so many online creators are chasing virality, numbers that were once extraordinary are now everyday. A decade ago, if you put a funny video of your dog on YouTube and it got a million views, that counted as a viral hit and you would probably find yourself on the news.

But nowadays, 1 million hits is nothing. Creators like MrBeast have worked so hard to optimise their videos' virality that they routinely hit hundreds of millions of views. When Feedback visited MrBeast's YouTube channel, the most recent video was "I Survived The 5 Deadliest Places On Earth". It had racked up 68 million views in eight days. That's a lot, but by MrBeast's standards, it's a bit mid, perhaps because none of the places proved deadly. The first was an African safari, which Feedback contends must be pretty survivable given that's where our species evolved.

Feedback is irresistibly reminded of Goodhart's law: the notion that, once you start using a given measure as a target, it stops being a useful measure. In this case, everyone is trying to make videos that get hundreds of millions of hits, so there are loads of videos with hundreds of millions of hits. It isn't at all clear that any of those videos are, in any meaningful sense, good or useful. But they sure do hoover up advertising money that could otherwise be used to support popular science magazines.

Twisteddoodles *for New Scientist*

Got a story for Feedback?
Send it to feedback@newscientist.com
or New Scientist, 9 Derry Street, London, W8 5HY
Consideration of items sent in the post will be delayed

Handle with kid gloves

One thing always guaranteed to start a shouting match on the internet is the question of global population. Long years in journalism have convinced Feedback that this topic is kryptonite for polite discussion.

The question is simple: how many people can Earth support? Feedback is fond of a 2012 review by the United Nations, which compiled 65 estimates of the maximum sustainable population. The most popular was about 8 billion (we're in trouble), but estimates ranged from fewer than 2 billion (we're totally screwed) to 1024 billion (we're fine). This question isn't well understood.

But that hasn't stopped many from taking a firm stance these days. On one side is the booming pro-natalist movement: a bunch of rich businesspeople who are going out of their way to have lots of children to assist the economy. Elon Musk is a keen pro-natalist, with more than a dozen kids and counting. His estranged daughter Vivian Wilson posted in February: "If I had a nickel for every time that I found out I had a new half-sibling online, I'd have a few nickels-which isn't a lot but it's weird that it happened SIX SEPARATE TIMES". A few weeks later she reshared her post, adding, simply, "Seven".

Set against these are the "populophobes" (Feedback is neologising all over the place today). Their idol is Paul Ehrlich, a lepidopterist who pivoted into scaremongering with *The Population Bomb*, the bestseller he co-authored in 1968. Ehrlich predicted global famines in the 1970s, and when they failed to appear, he spent decades insisting he was right anyway.

On paper, it seems like the pro-natalists ought to win by simply outbreeding the populophobes, but what if their kids disagree?

A knotty problem

One of Feedback's pet peeves is the weird way that shoe shops lace up shoes. Whenever we buy a new pair, we have to unlace them completely and start from scratch.

So we turned with relief to a paper by particle physicist Rodrigo Alonso that asks: "how many topologically different ways are there to tie your laces?"

Blessed relief, we thought: a solution. And then we tried to read the paper. On page two, Alonso defines, "For convenience", an equation that answers this question for any number of holes. It is the sort of equation that would have given us the heebie-jeebies back when we did advanced maths at school.

Then he proceeds to show that his formula for permutations of shoelaces can be applied to problems in particle physics, telling us to "consider a $O(n)$ symmetric theory of a scalar with n components Φ_i in d spacetime dimensions with an interaction term in the Lagrangian density L and $2Q$-point contact-interaction amplitude". We'd rather not.

Still, at least this explains the weird lacing patterns used by shoe shops: they're trying to finally prove string theory.