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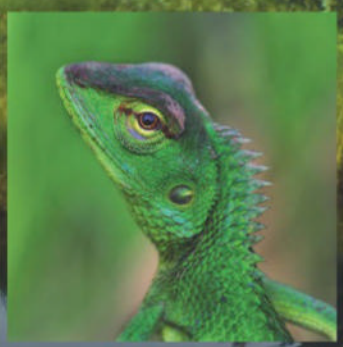

Insect and ecosystems safari: Sri Lanka

30 March 2026 | 11 days

Explore Sri Lanka's natural world on a science-rich expedition through its varied ecosystems, led by entomologist Dr Tim Cockerill.

- Discover endemic insects, rare birds and elusive wildlife on private walks, night safaris and safaris in Udawalawe and Sinharaja national parks, while learning about the ecological forces that shape these extraordinary habitats
- Travel through lush tea country, visit UNESCO-protected forests and stay in eco-lodges, gaining rare, hands-on insight into the island's rich biodiversity

Alaskan brown bear, ecology and wilderness adventure: US

9 August 2026 | 6 days

Venture into the wild heart of Alaska for an unparalleled encounter with brown bears in their natural environment.

- From a secluded fly-in bush camp surrounded by Lake Clark National Park, observe these apex predators at remarkably close range from grazing in lush meadows to fishing for salmon in tidal streams
- Guided by expert naturalists, you'll gain fascinating insights into bear ecology, behaviour and the delicate balance of this untamed ecosystem

An expedition through unique ecosystems: Madagascar

5 September 2026 | 16 days

Immerse yourself in Madagascar's diverse and unique ecosystems, a living laboratory of evolution and biodiversity that includes 23 species of lemur.

- Explore the country's rich flora and fauna, which have evolved in isolation, leading to unique adaptations and species found nowhere else on Earth
- Gain a deeper understanding of how, having broken away from mainland Africa some 150 million years ago, Madagascar is now unlike anywhere else on the planet

Yellowstone National Park and Grand Teton wildlife safari: US

28 July 2026 | 5 days

Explore Yellowstone like never before on a science-curious expedition led by expert guides through the iconic Lamar Valley, the "American Serengeti".

- Track elusive wolf packs, witness vast herds of bison and elk and spot grizzlies and eagles in their natural habitat, all while gaining insight into the ecology, behaviour and predator-prey dynamics that shape this extraordinary landscape
- From sweeping sagebrush valleys to geyser-dotted plains, each day is crafted to maximise wildlife encounters

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This week's issue

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"The implication is startling: gravity may not be a fixed, universal force at all"

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Views

SHUTTERSTOCK/SKREIDZELEU

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The back pages

Infection, anyone?

Human challenge trials have never been more popular

ROOMS AVAILABLE: minimum two-week stay, en-suite. Free pool. Meals, Wi-Fi and infectious virus included. Call now!

Would you answer an ad like that? What about one offering the promise of violent diarrhoea? How many stars worth of service would tempt you to add a sexually transmitted infection to your stay? Perhaps a nice monetary payment would help?

Welcome to the bizarre world of human challenge trials – coming soon to a biosecure quarantine facility near you.

Boosted by the collective nightmare of the covid-19 pandemic, an increasing number of researchers are asking healthy people to sign up for experiments that deliberately make them sick. And from dysentery and cholera to gonorrhoea, volunteers are agreeing to catch diseases in greater numbers than ever before.

As we discuss on page 38, the trials are a quick and relatively cheap way to test vaccines and treatments and track the progress of infections. They also aren't as dangerous as they might sound. The trials only get the go-ahead under strict medical supervision and if the symptoms can be quickly doused with effective therapies.

"Deliberately infecting healthy volunteers isn't risk-free, nor are the ethics clear-cut"

But they aren't risk-free, nor are the ethics clear-cut. Unlike people with an illness agreeing to try an experimental drug that might cure them, challenge trials aim to make people feel worse, even if just for a short time, with little or no direct medical benefit in return.

And it isn't always possible to guarantee there will be no enduring effects. Some ethicists, for example, are still unhappy that UK scientists carried out challenge trials with covid-19 during the pandemic, because of the risks of the chronic symptoms of long covid.

But the pandemic also highlighted the enormous positive value and impact of vaccines. Data gathered so far suggest human challenge trials are safe, especially for the young and healthy. As these studies could speed the development of new protections against long-standing scourges, including malaria, Zika and norovirus, the only real challenge should be: how can we do more? ▮

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New Scientist Discovery Tours

Unique journeys for curious minds

Science of astronomy and the northern lights: Sweden

18 March 2026 | 5 days

Travel with astronomy expert Jamie Carter to the Arctic and discover the wonders of the night skies and the northern lights, with stargazing sessions under some of the clearest skies on Earth.

- Uncover the fascinating physics behind the northern lights from experts at the Aurora Sky Station
- Experience sleeping on ice at the world's coolest hotel, where you'll stay in artfully crafted rooms sculpted entirely from ice and snow

A geological journey through ancient landscapes: Vietnam

11 April 2026 | 13 days

Journey through Vietnam's deep history and visit some of Southeast Asia's most outstanding geological sites. Uncover remarkable feats of underground engineering and savour the country's rich culinary heritage.

- Explore the historic cities of Hanoi and Hue and cruise across Ha Long Bay, a UNESCO World Heritage Site
- Visit leading conservation centres, supporting rare and endangered primates found only in Vietnam

Uncovering Vesuvius, Pompeii and ancient Naples: Italy

17 April 2026 | 6 days

Step into a world where history, archaeology and volcanology collide on a thrilling journey through Naples, Pompeii, Herculaneum and the slopes of Mount Vesuvius.

- Guided by expert volcanologist Christopher Kilburn, this tour offers the opportunity to see legendary sites
- Walk part of the trails to Mount Vesuvius for breathtaking views of the Bay of Naples while learning about the volcano's explosive history and ongoing activity

Megalithic Malta: Temples, architecture and archaeology

21 April 20256 | 6 days

Explore Malta and Gozo accompanied by award-winning journalist Juliet Rix. The islands are home to exceptional archaeological sites including prehistoric temples that are thought to be the earliest accessible free-standing buildings in the world.

- Visit the megalithic temple complexes of Tarxien, Hagar Qim and Mnajdra, which date back to around 3600 BC
- Discover the stunning fortified cities of Valletta, Mdina and Victoria

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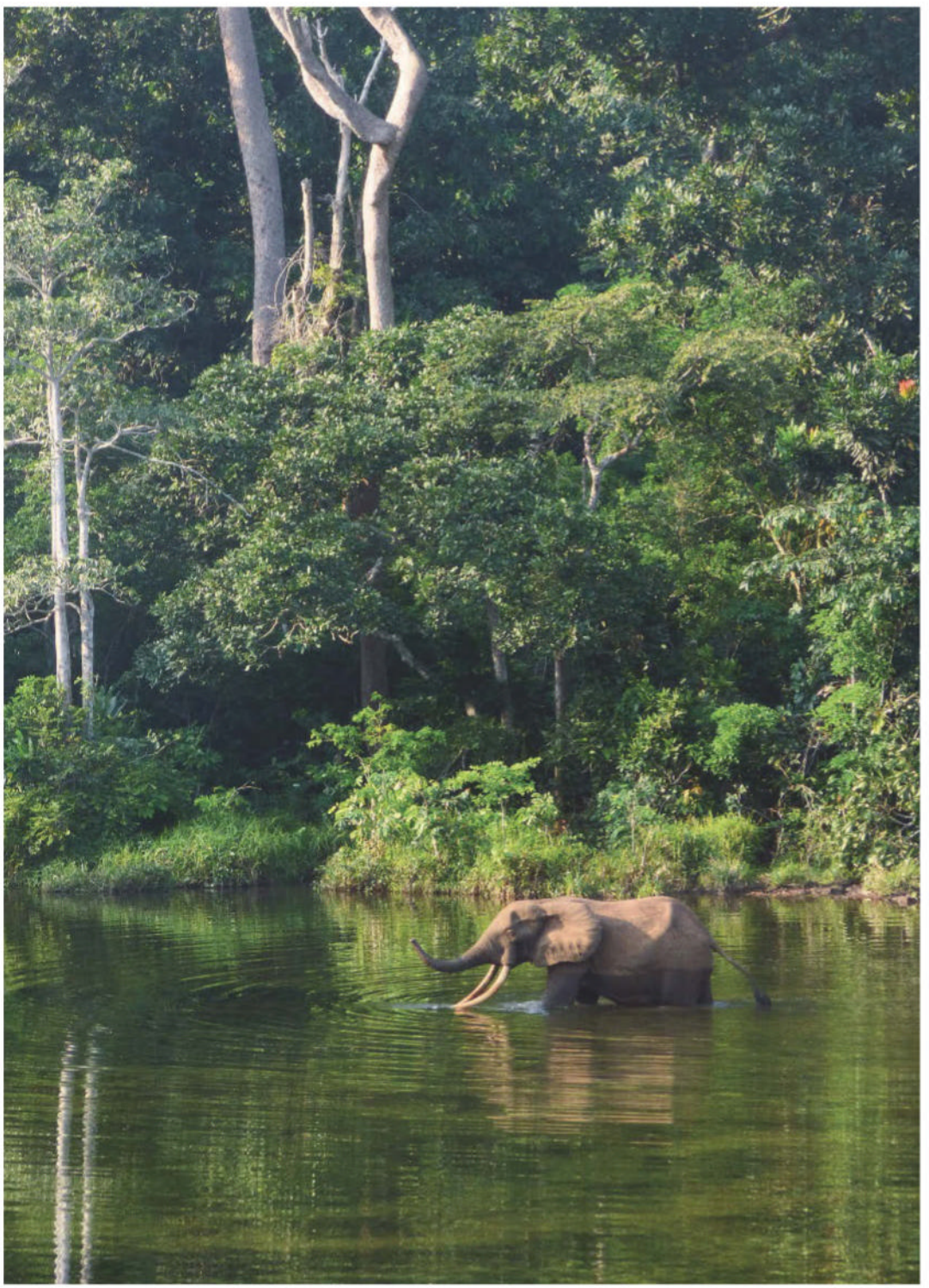


F. MAISELS/WCS

Conservation

Counting elusive elephants

The secretive African forest elephant is coming out of the shadows. The latest IUCN assessment of the species, which lives in dense rainforest, concludes there are over 135,000 of them, 16 per cent more than at the last count in 2016. This increase is mainly due to a more accurate counting method: analysing elephant faeces for DNA. Despite this, the species is still critically endangered due to poaching.

Health

Pregnancy alters mouth bacteria

Dental problems often arise during pregnancy, and rapid changes to the oral microbiome could be partly to blame, finds **Chris Simms**

"GAIN a child, lose a tooth", or so the saying goes. Pregnancy is known to be linked to a higher risk of dental issues, but we aren't entirely sure why. Now, researchers have found that the oral microbiome changes while a woman is expecting, becoming less diverse and potentially more prone to causing inflammation.

The hormonal upheaval during pregnancy is generally blamed for the higher risk of conditions like gum disease and tooth decay. A common idea also states that fetuses take calcium from their mother's teeth, although this isn't backed up by evidence.

Disruptions to the oral microbiome, which is made up of more than 700 species of bacteria, can cause dental problems, regardless of whether or not someone is pregnant. But Yoram Louzoun at Bar-Ilan University in Israel and his colleagues wanted to understand whether this generally stable ecosystem changes during pregnancy, so they collected saliva samples from 346 women from Israel at 11-14 weeks, 24-28 weeks and 32-38 weeks of pregnancy, representing all three trimesters.

The researchers saw a drop in the diversity of species in the saliva samples as early as the transition between the first and second trimester – and it then decreased progressively throughout the rest of the pregnancy. Key features included a reduction in the numbers of the species *Akkermansia muciniphila*, often thought of as a "good bacterium", and an increase in Gammaproteobacteria and Synergistota bacteria, which are linked to inflammation.

"Typically, the oral microbiome is stable, but over many years, there is a slow decrease in diversity," says Louzoun. "Pregnancy is like a fast-forward of that very slow evolution. You can see the changes that normally happen over many years in just nine months."

FLY VIEW PRODUCTIONS/GETTY IMAGES

Pregnancy is linked to a heightened risk of dental issues

There are many possible reasons for why these changes – albeit small – happen. "You'll have lots of things going on during your pregnancy, like changes in hormones and inflammation, which will also alter the microbiome," says Lindsey Edwards at King's College London. "And obviously, during pregnancy, you are often changing your diet. You might also feel nauseous and not be eating, and you may also stop taking medications if you know that you're pregnant. All of these could have effects."

The women completed dietary and health questionnaires, which allowed the researchers to identify distinctive but similar effects among certain women, such as those who said they ate a gluten-free diet, took antibiotics, were stressed or were current or ex-smokers. "Most women stop smoking when they're pregnant, but you see the effect of the fact that they used to smoke, perhaps nine months ago, in the microbiome," says Louzoun. "It has a really long-term effect."

Comparable changes were evident in a second experiment, where the researchers examined the oral microbiomes of 154 pregnant women from Russia during their second and third trimesters (bioRxiv, doi.org/qggb).

> **"Changes to the oral microbiome that normally happen over many years are seen in nine months"**

Although pregnancy is known to increase the risk of dental issues, Louzoun doesn't necessarily think changes to the oral microbiome are behind this, given that such problems can start very early in pregnancy. "I cannot really say if all these microbiome changes are positive or negative, but they definitely are fast," he says.

Yet Edwards says the microbial changes might be a factor, noting that saliva also becomes more acidic during pregnancy, altering its bacterial species.

Immune changes

Valentina Biagioli at the University of Genoa in Italy says changes to the oral microbiome and hormone levels throughout the body could both play a part, because they interact with and affect each other. "There is a plausible biological rationale connecting the observed changes in the oral microbiome to the most common dental problems reported during pregnancy, including tooth loss," she says.

Disruptions to the oral microbiome have been linked to pregnancy complications, so if we establish what an optimal version of this ecosystem looks like, it could be used to gauge how a pregnancy is progressing. "Once we have the baseline oral microbiome of pregnancy, it can be used to detect deviations," says Louzoun.

We are also learning more about this microbiome's role in the immune system, which could affect the health of both pregnant women and their fetuses. "The microbiome is helping to educate your immune system and it's a bidirectional link," says Edwards.

Better understanding how to maintain your oral microbiome – such as good dental hygiene and diet – could therefore have lasting implications. "Changes to the microbiome might determine a parent's inflammatory status and help prime the child's immune system, either inducing long-term health or potentially impacting allergy risk, infection susceptibility or development of long-term, chronic inflammatory conditions," says Edwards.

Evolution

Our feline friends spread around the world later than expected

James Woodford

GENETIC evidence has revealed that domestic cats originated in North Africa and spread to Europe and East Asia in the past 2000 years, more recently than previously thought.

Domestic cats (*Felis catus*) are descended from the African wildcat (*Felis lybica lybica*) and today they are found on every continent except Antarctica.

Previous research has suggested that domestic cats originated in the Levant and may have arrived in Europe as early as 9600 BC.

Claudio Ottoni at the University of Rome Tor Vergata in Italy and his colleagues studied 225 ancient cat specimens from nearly 100 archaeological sites in Europe and what is now Turkey. From these, they obtained 70 genomes, spanning from the ninth millennium BC to the 19th century AD. They also obtained 17 genomes of museum specimens and present-day wildcats from Italy, Bulgaria, Morocco and Tunisia.

The earliest cat the team genetically identified as an African wildcat or a domestic cat was a specimen from Sardinia, Italy, radiocarbon dated to the second century AD (*Science*, doi.org/hbcx42). All earlier cats in Europe were genetically European wildcats (*Felis silvestris*).

KATHO MENDEN/ALAMY

Wherever they evolved, domestic cats always prefer the sun

This shows that the dispersal of domestic cats occurred much later than previously thought.

Ottoni says Mediterranean civilisations during the first millennium BC were primarily responsible for the spread of African wildcats, which involved at least two genetically distinct populations. One probably comprised wildcats from north-west Africa that were introduced to Sardinia and founded the present-day wildcat populations on the island. The second went on to become the genetic forerunners of modern domestic cats.

"At the beginning of the domestication process, cats were probably very good at adapting to the human environment," he says. "Their ecological plasticity made them very successful. They could thrive with humans in different conditions."

In a second study, Shu-Jin Luo at Peking University in China and her colleagues studied 22 sets of feline remains from China, spanning a period of over 5000 years, and analysed the genomes of 130 modern and ancient Eurasian cat specimens.

They were surprised to find that over 5000 years ago, a different species of cat lived closely with people: the leopard cat (*Prionailurus bengalensis*), a small wildcat native to East Asia.

"These cats frequented human settlements, likely drawn by rodents, but they were never truly domesticated," says Luo.

"Cats' ecological plasticity made them very successful. They could thrive with humans"

The study found that true domestic cats arrived in China much later, around 1300 years ago. Genomic evidence links them to cats from the Middle East and Central Asia, suggesting they were introduced to China along the Silk Road by traders (*Cell Genomics*, doi.org/qggj).

Despite a relationship lasting more than 3500 years, leopard cats ultimately never became domesticated and returned to their natural habitats, says Luo. ▮

Chemistry

Plastic can be programmed to self-destruct

CHEMICAL additions to plastic that mimic DNA can create materials that break down in days, months or years rather than littering the environment for centuries.

In 2022, more than a quarter of a billion tonnes of plastic was discarded globally, and only 14 per cent was recycled – the rest was burned or buried.

Yuwei Gu and his colleagues at Rutgers, The State University of New Jersey, are developing a technique to create plastics with finely tuned lifespans that could quickly break down either in compost or in the natural environment.

Gu wondered why natural, long-stranded polymers like DNA and RNA can break down relatively quickly, but synthetic ones, such as plastics, can't, and if there was a way to replicate their process.

Natural polymers contain chemical structures known as neighbouring groups that aid in deconstruction. These structures power internal reactions called nucleophilic attacks that sever the bonds in polymer chains – something that requires a great deal of energy with normal plastics.

IAIN MASTERTON/ALAMY

Only 14 per cent of the plastic we discard each year is recycled

Gu and his team created artificial chemical structures that mimic these neighbouring groups and added them when making new plastics. They found that the resulting material could break down easily and that by altering the structure of the additions, they could fine-tune how long the material remained intact before deconstructing (*Nature Chemistry*, doi.org/hbcxs8).

After the plastic breaks down, the long polymer chains are converted into small fragments, which Gu hopes will either be used to make new plastics or will safely dissolve into the environment. ▮

Matthew Sparkes

Space

First hints of dark matter stars...

Huge stars powered by dark matter instead of nuclear fusion could solve several mysteries of the early universe, reports **Leah Crane**

WE MAY have seen the first signs of strange stars powered by dark matter. These so-called dark stars could explain several of the most mysterious objects in the universe, while also giving us clues about the true nature of dark matter itself.

Normal stars form when a cloud of gas collapses in on itself and the centre gets so dense that it sparks nuclear fusion. That fusion powers the star by pumping huge amounts of heat and energy into the surrounding plasma and gas.

Dark stars could have formed in a similar way in the early universe, when everything was denser, especially dark matter. If the cloud that collapsed to form a star had enough dark matter inside, the dark matter would begin smashing together and annihilating well before fusion could start, emitting enough energy to make the dark star glow and keep it from collapsing further.

REMOTEVFX/GETTY IMAGES

A dark star would glow due to dark matter annihilating

The formation of a dark star would be fairly straightforward, and now a team led by Katherine Freese at the University of Texas at Austin has worked out what its demise might look like.

In a massive regular star, once hydrogen and helium run out, the star goes on to fuse together heavier elements until it runs out of fuel and collapses to form a black hole. The more material you throw into the star, the faster this process takes place.

Not so for dark stars. "You can take an ordinary, solar-mass sort of star, put some dark matter into it so the power source for that star is not nuclear reactions but dark matter annihilation, and you can keep feeding it. As long as you keep feeding it with enough dark matter too, it'll never go through the nuclear evolution that gets it in trouble," says George Fuller at the University of California, San Diego, who was part of the team.

But thanks to general relativity, dark matter can only save these strange giants for so long. According to Albert Einstein's theory, the gravitational field of an object doesn't grow straightforwardly with mass – gravity begets more gravity. Eventually, an object gets so big that it becomes unstable, and any small perturbation can cause gravity to take over and collapse it into a black hole. The researchers calculated that for dark stars, this should happen at masses between 1000 and 10 million times that of the sun (arXiv, doi.org/qgfv).

That mass range makes supermassive dark stars an excellent contender to explain one of the great mysteries of the early universe: supermassive black holes. Astronomers have spotted enormous black holes extremely early in the universe's history, but it is unclear how they could have formed so quickly. One of the leading hypotheses is that rather than forming from normal stars, they were made from some sort of enormous "seed".

"If you have a black hole of 100 solar masses, how the hell are you going to get up to 1 billion solar masses in a few hundred million years? It's just not possible if you're only making black holes from standard stars," says Freese. "Whereas, if you're starting with pretty big seeds, that really makes a difference." Dark stars could be those seeds.

"If stars made from dark matter are out there, they are rare. Rare, but extraordinary"

That isn't the only mystery in the early universe that could be addressed by dark stars. The James Webb Space Telescope (JWST) has spotted two other unexpected types of objects, which have been nicknamed little red dots and blue monsters, respectively. They are extremely distant objects and the immediate explanation for each is that they are compact galaxies.

Like supermassive black holes, though, these objects are too distant, and therefore too early in the universe's history, for us to easily explain how they formed – there simply hadn't been enough time. From the observations we have of them, Freese and another group of colleagues calculated that both little red dots and blue monsters could be individual, extremely massive dark stars (arXiv, doi.org/qgfx).

If they are dark stars, there should be a signature in their light. This signature has to do with a particular wavelength of light that dark stars, if they exist, should absorb. Regular stars – and galaxies full of them – are too hot to absorb this light.

Freese and her colleagues found hints of that absorption in initial JWST observations of several of these objects, but the data is too noisy to say for sure that it is there. "Right now, all the candidates that we have, there are two things that could fit the spectra equally well: one supermassive dark star or an entire galaxy of regular stars," says Freese. "If you see this one dip, for sure that is not one galaxy full of

normal stars, that is a dark star. But for now all we have is a pathetic little hint."

We cannot say that we have definitely detected dark stars yet, but this is a step forward. "This isn't some profound, unambiguous smoking gun, but it's a really well-motivated thing that they're looking for, and there are some aspects of what JWST is seeing that do point in that sort of direction," says Dan Hooper at the University of Wisconsin-Madison.

Mystery solvers

To determine whether or not these objects really are dark stars, we will need more observations, ideally at higher sensitivities, but it isn't clear whether JWST is capable of reaching the necessary level of detail for galaxies – or dark stars – this far away.

"Confirming dark star existence would be a major discovery," says Volodymyr Takhistov at the High Energy Accelerator Research Organization in Japan. It could open a new observational window on fundamental physics, he says. That is because dark stars could not only solve the cosmic mysteries of supermassive black holes, little red dots and blue monsters, but we could also use them to probe the nature of dark matter, about which we currently know very little.

That is particularly the case if they are the seeds for supermassive black holes. Freese, Fuller and their team calculated that the mass at which they would collapse and form black holes is dependent on the mass of the dark matter particles annihilating at their cores. This means we could use supermassive black holes to measure, or at least constrain, the properties of dark matter. Of course, first we have to confirm that dark stars even exist.

"If these things are out there, they're rare," says Hooper. "Rare, but extraordinary." ▮

Space

... and of what dark matter itself is made of

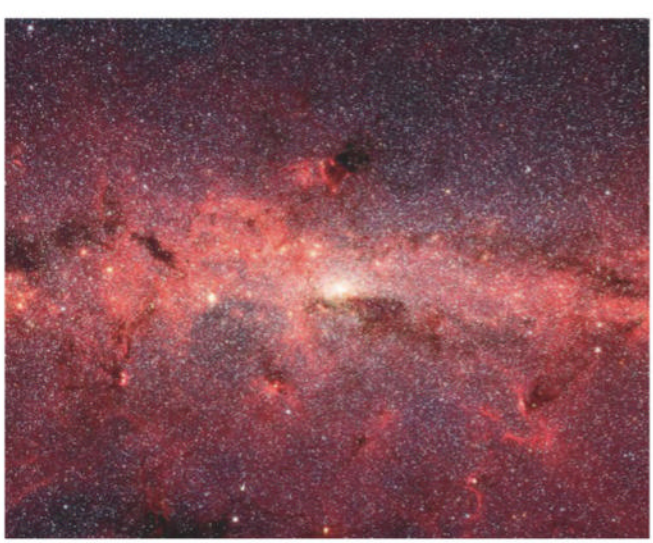
Alex Wilkins

AN UNEXPLAINED glow that appears to emanate throughout the Milky Way's outer regions could be our first glimpse of what dark matter is made of, but astronomers say it is too early to know for sure.

Dark matter is thought to make up 85 per cent of all mass in the universe, but physicists have never been able to detect the particles that constitute it.

One leading candidate for dark matter is the weakly interacting massive particle (WIMP). These hypothetical particles are difficult to detect because they interact so rarely with regular matter, but theorists predict that they should occasionally self-annihilate, disappearing and producing a flash of high-energy radiation in the form of gamma rays.

If dark matter is distributed throughout our galaxy, as its gravitational pull suggests, and it is also made up of WIMPs, then we should see a glow from the WIMPs self-annihilating.



The Milky Way is thought to be filled with dark matter

NASA, JPL-CALTECH, SUSAN STOLOVY (SSC/CALTECH) ET AL.

Astronomers have argued for more than a decade over whether a strange excess of gamma-ray radiation from the centre of our galaxy could be this signal, but the evidence is still inconclusive.

Now, Tomonori Totani at the University of Tokyo claims he may have detected such a signal coming from the outer part of the Milky Way, known as its halo, using 15 years of observations from NASA's Fermi Gamma-ray Space Telescope (*Journal of Cosmology and Astroparticle Physics*, doi.org/qgf4).

> **"This is the most promising candidate radiation from dark matter known to date"**

Totani first produced a model of how much gamma-ray radiation there should be in this region based on known sources, such as stars, cosmic rays and large bubbles of radiation seen above and below the Milky Way. Then he subtracted this radiation from the amount seen by the Fermi telescope, finding there was a leftover gamma-ray glow with an energy of around 20 gigaelectronvolts.

A gamma-ray signal with this energy fits what could come from a particle self-annihilating in the energy range that WIMPs are predicted to have, says Totani. While he admits that it is too early to definitively conclude that the gamma-ray spike is coming from dark matter, he says that the signal is "the most promising candidate radiation from dark matter known to date".

"Even though the research began with the aim of detecting dark matter signals, I thought it was like playing the lottery. So when I first spotted what seemed like a signal, I was sceptical," says Totoni. "But when I took the time to check it meticulously and felt confident it was correct, I got goosebumps."

"It's a result that certainly deserves further study, but drawing firm conclusions now would be premature," says Francesca Calore at the French National Centre for Scientific Research in Annecy. It is difficult to accurately make a model of all gamma ray sources in the Milky Way other than dark matter, she says.

Silvia Manconi at Sorbonne University in France says we haven't seen such gamma-ray signals from other sources where we should have, such as dwarf galaxies, so that discrepancy would need to be explained.

We would need to look at many other radiation sources, such as radio waves and neutrinos, to be sure that the gamma rays aren't coming from something else, says Anthony Brown at the University of Durham, UK. "It is only looking from one angle," he says. "Dark matter really needs as much high-quality data as you can get." ▮

Environment

Have we found a greener way to do deep-sea mining?

Alec Luhn

A PROCESS to extract metals from their ore with hydrogen could make deep-sea mining more sustainable than mining on land, a new study claims.

Swathes of the ocean floor are littered with nodules the size of tennis balls made largely of manganese, with some nickel, copper, cobalt and other elements. As the construction of solar power and electric vehicles booms, demand for these metals is rising. But plans to mine for the nodules are controversial as operations to collect them would potentially harm the deep-sea floor – one of the last pristine ecosystems.

Even so, some researchers suspect deep-sea extraction will eventually take place. "I think there is a good chance that someday people... will mine the nodules," says Ubaid Manzoor at the Max Planck Institute for Sustainable Materials in Germany. "So better to have a good process [for extracting metals] after mining than to have one more dirty process."

The Metals Company, a Canadian deep-sea mining firm that has applied for a deep-sea mining permit from the Trump administration, plans to extract metals using a fossil fuel-based approach involving coke and methane. Its process involves placing the nodules first in a kiln and then an electric arc furnace – a greener alternative to a traditional blast furnace. Even so, the company says its approach will produce 4.9 kilograms of carbon dioxide emissions for every 1 kilogram of valuable metals.

"It's better to have a good process for extracting metals after mining than to have a dirty process"

Manzoor and his colleagues have found a way to lower these extraction-related emissions. Their system doesn't involve a kiln. Instead, the nodules would be ground into smaller pellets and placed straight into an arc furnace that also contains hydrogen and argon gas. High-energy electrons flowing from an electrode in the furnace to the pellets would knock electrons off the molecules of hydrogen gas, forming a plasma that can be heated up to temperatures exceeding 1700°C.

The hydrogen ions in the plasma then react with the oxygen in the pellets, stripping the oxides away from the alloy and leaving pure metal behind. Besides water, the only by-products are manganese compounds that can be used for making batteries and steel.

If the hydrogen gas used in the furnace is "green" – meaning it is produced by splitting water with electricity from renewable sources – and the electricity to run the furnace is generated from renewables, the process should emit no CO_2, according to the researchers (*Science Advances*, doi.org/hbcxrg). Today, the vast majority of hydrogen is produced using fossil fuels.

Metals like manganese are found on land as well as on the sea floor, but at concentrations about 10 times lower. Mining them on land can result in razed rainforests and polluted rivers.

However, land-based mining could be better regulated to prevent environmental damage, and the smelting of metals could be done with green hydrogen and renewable electricity rather than fossil fuels, says Mario Schmidt at Pforzheim University in Germany. "We do not see any fundamental advantage for deep-sea mining in terms of carbon footprint," he says.

Manzoor stresses that the environmental impacts of deep-sea mining should be investigated. ▮

Archaeology

Droughts led to the collapse of the Indus Valley Civilisation

CLIMATE warming and severe droughts dealt a death blow to the Indus Valley Civilisation, a mysterious urban culture that flourished around 4000 years ago in what is now Pakistan and India.

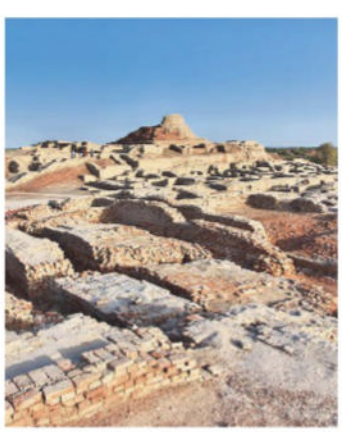
This culture developed settlements along the Indus river and its tributaries. It built several cities and is also known as the Harappan civilisation after Harappa, a city that had a population of 35,000, huge for the time.

While we don't fully understand the script they used, the Harappans are known for water management like giant storage cisterns and sewage systems of terracotta pipes and brick channels. But these techniques couldn't withstand a millennium of hot, dry conditions.

"Four different droughts occurred in between pre-Harappan to later Harappan periods," says Vimal Mishra at the Indian Institute of Technology Gandhinagar. "In response to these events, there has been a continuous migration towards where the water availability was better."

Previous research had suggested that monsoon rains weakened in the Indus valley after a global megadrought 4200 years ago, precipitating the civilisation's collapse. Mishra and his colleagues argue that it was a more gradual fragmentation.

The scientists estimated rainfall across the region using three climate models and compared this with rainfall estimates derived from stalactites and stalagmites, as well as lake sediments.



SERGEY-73/SHUTTERSTOCK

The Harappans built settlements along the Indus river

The findings showed that four droughts lasting at least 85 years hit the Indus Valley Civilisation between 4400 and 3400 years ago. Temperatures also rose by about 0.5°C (*Communications Earth & Environment*, doi.org/hbcv5p).

The level of the Indus river fell, additional modelling showed. The Harappans, who are believed to have prayed to rivers and irrigated crops like wheat and barley with their annual floods, clustered closer to waterways. When more droughts followed, they abandoned their cities and migrated towards the Himalayan foothills and the Ganga river plain. ▮

AL

Life

We may need a fourth law of thermodynamics

Karmela Padavic-Callaghan

THE physics of thermodynamics, which involves quantities like heat and entropy, offers tools for determining how far from equilibrium an idealised system of particles is. But when it comes to life, it isn't clear that our current thermodynamical laws are enough. Now, scientists may have taken the first step towards creating a new one.

Thermodynamics is important for life, because being out of equilibrium is one of its key properties. But because cells are filled with molecules that actively consume energy, a cell's state is different from, say, a bunch of beads floating in a liquid. For instance, cells have a "set point", which means they behave as if they are following an internal thermostat. There is a feedback mechanism that brings them back to the set point, which lets them keep functioning. It is this kind of behaviour that may not be easily captured by classical thermodynamics.

To find out how disequilibrium in living systems differs from the state of disequilibrium in a non-living system, N Narinder and Elisabeth Fischer-Friedrich at the Dresden University of Technology in Germany turned to HeLa human cells – a line of cancer cells commonly used in scientific research that were taken without consent from a woman called Henrietta Lacks in the 1950s.

First, the researchers used chemicals to stop the cells midway through cell division. Then they probed their outer membranes with the tip of an atomic force microscope to assess how fluctuations in each cell's membrane changed when the researchers interfered with some of the cell's processes.

They discovered that, for these fluctuations, one standard thermodynamic "recipe" that would explain the behaviour of a non-living system wasn't fully accurate. Specifically, the idea of "effective temperature" proved imprecise. This is an idea meant to capture something similar to our understanding of how temperature increases when we take a system like a pot of water out of equilibrium by heating it.

The team concluded that a more useful quantity for capturing the degree of life's disequilibrium is "time reversal asymmetry" (*Physical Review X*, doi.org/qgrp). This property explores the extent to which a biological process would differ if it ran backwards instead of forwards in time. The presence of time reversal asymmetry might be directly related to the fact that biological processes serve a purpose such as survival and proliferation, says Fischer-Friedrich.

> "When it comes to life, it isn't clear that our thermodynamical laws are enough"

"We know in biology that there's a lot of processes that really rely on a system being out of equilibrium, but it is actually important to know how far a system is out of equilibrium," says Chase Broedersz at Free University Amsterdam in the Netherlands. The new study identifies valuable new tools for pinning that down, he says.

Ultimately, the team wants to derive something akin to a fourth law of thermodynamics that is only applicable to living matter where processes have a set point, says Fischer-Friedrich. ▮

Ancient humans

Ancient foot mystery may finally be solved

James Woodford

YOHANNES HAILE-SELASSIE

This foot had an opposable big toe, suggesting its owner could climb trees

THE provenance of 3.4-million-year-old foot bones in Ethiopia may have been discovered.

In 2009, Yohannes Haile-Selassie at Arizona State University and his colleagues found eight hominin bones that once made up a right foot at a site known as Burtele in the Afar region of north-eastern Ethiopia. The find, named the Burtele foot, included a gorilla-like opposable big toe, suggesting that the species it belonged to was able to climb trees.

Although an ancient hominin species, *Australopithecus afarensis*, was known to live nearby – most famously represented by the fossil Lucy – the Burtele foot seemed to be from a different species. "We knew from the very beginning that it didn't belong to Lucy's species," says Haile-Selassie.

The two main possibilities were that the foot belonged to another species within the *Australopithecus* genus or a much older, more primitive one called *Ardipithecus*, which inhabited Ethiopia more than a million years earlier, but also had an opposable big toe.

The recovery of jaw and teeth remains from the same locality led the researchers to announce the discovery of a new hominin species in 2015, which they named *Australopithecus deyiremeda*. They suspected that the mysterious foot bones belonged to *A. deyiremeda*, but these were a different age to the jaw and teeth remains, so the team couldn't be sure.

But the next year, the team found an *A. deyiremeda*'s lower jawbone within 300 metres of where the foot was recovered, with both remains being the same geological age. Based on this, the team has concluded that the foot bones belonged to *A. deyiremeda*.

The researchers then studied the carbon isotopes of the *A. deyiremeda* teeth and found that the species mostly consumed material from trees and shrubs, whereas teeth of *A. afarensis* indicate a diet much richer in grasses (*Nature*, doi.org/hbct8m).

The discoveries prove that two species of hominin lived together in the same environment, says Haile-Selassie. The groups weren't competing for food, so it is possible they coexisted peacefully, he says. "They must have seen each other, spent time in the same area doing their own things." ▮

Climate change

Africa's forests have become a carbon source

Alec Luhn

AFRICAN forests are now emitting more carbon dioxide than they absorb, a fundamental shift that will make it more difficult for the world to cut its net emissions to zero.

Forests and shrubby woodlands on the continent have previously been one of the world's biggest carbon sinks, accounting for 20 per cent of all the CO_2 taken up by plants. The lion's share of this is in the Congo rainforest, the second largest in the world after the Amazon. Sometimes called the "lungs of Africa", it absorbs an estimated 600 million tonnes of CO_2 per year. However, that number has been falling as the rainforest is destroyed by logging and mining.

Now, researchers have found that after gaining biomass from 2007 to 2010, African forests lost 106 million tonnes of biomass per year from 2011 to 2017. That is equivalent to roughly 200 million tonnes of CO_2 emissions per year (*Scientific Reports*, doi.org/hbcw7h). This was driven by deforestation in the Congo rainforest, says Heiko Balzter at the University of Leicester, UK. "If we are losing the tropical forests as one of the means of mitigating climate change, then we basically have to reduce our emissions of greenhouse gases from fossil fuel burning even faster to get to near-zero emissions."

Balzter and his team estimated the amount of biomass with satellite measurements of the colour and moisture content of the forest canopy, as well as its height at certain points. They compared this with measurements on the ground, although these are sparse in Africa. But Simon Lewis at University College London says satellite data can't detect the type of trees in a forest and isn't reliable for estimating the carbon absorbed by high-biomass intact forests or emitted in forests degraded by selective logging. A dense hardwood like mahogany might hold more carbon than a light balsa wood of the same size, for instance.

GUENTERGUNI/GETTY IMAGES

The Congo rainforest is the second largest in the world

"Deforestation in the Democratic Republic of the Congo... is higher than it was in the 2000s," he says. "But whether that is enough to tip the carbon balance of the entire continent is unknown."

106

million tonnes of biomass are lost from African forests annually

However, the study didn't include the wet peatlands found underneath much of the Congo rainforest, which absorb a small amount of CO_2 each year and hold about 30 billion tonnes of ancient carbon.

The Amazon rainforest, which was also once a major carbon sink, emitted more CO_2 than it absorbed in several recent years. But whereas deforestation in the Amazon has fallen under a government crackdown, it has been growing in the Congo rainforest.

In the Democratic Republic of the Congo, small-scale miners often destroy the rainforest to dig up minerals like gold. Companies, many of them foreign-owned, illegally log colourful hardwoods like African teak and coralwood.

At the COP30 climate summit last month, Brazil announced the Tropical Forests Forever Facility, a fund that will pay its investment returns to tropical countries at $4 per hectare of forest left standing. But so far countries have donated only $6.6 billion to the fund, far short of the $25 billion goal.

"It's really important to make this Tropical Forest Forever Facility work, to try and reverse this trend of the African tree biomass actually releasing carbon into the atmosphere," says Balzter. ▮

Animal behaviour

Cats overcome fear of water to benefit from aquatic therapy

Christa Lesté-Lasserre

CATS with injuries and disabilities can benefit from underwater treadmill therapy and swimming pools without fear, thanks to a newly developed training protocol.

"It's amazing, really, because it comes down to a matter of familiarisation," says Stefania Uccheddu at San Marco Veterinary Clinic and Laboratory in Padua, Italy. "Cats just don't know what water is. But when cats get familiar with the physiotherapy environment, water is no longer a problem."

Underwater treadmills and swimming pool therapies allow people and animals to exercise while bearing less weight, making it an ideal form of rehabilitation and strength training. But cats often experience stress when faced with water, possibly because they evolved in the desert.

In the new training programme, Uccheddu and her colleagues first let the cats explore the room and dry equipment, then feel a moist towel on their paws. Later, they heard the treadmill and stood in increasingly deeper water, always with the owner nearby. The team rewarded the cats at each step with a prize, such as food, petting or a toy (*Applied Animal Behaviour Science*, doi.org/qgrt).

The group selected 12 of their clinic's feline patients with neurological or orthopaedic disease to test their training programme. Throughout, they monitored each cat for specific stress behaviours like meowing. They stopped the session if the cat showed more than five of these behaviours in a minute.

All 12 cats successfully completed their rehab programmes, which, depending on their issues, lasted from a few weeks to a year, says Uccheddu. And each animal showed significant physical improvement, with some making full recoveries and others being well enough to climb trees again. ▮

Chip sale may shake up the AI industry

Google is reportedly in talks to sell its custom computer chip designed for AI to other tech firms, a move that could unsettle the dominant chip-maker Nvidia, reports **Alex Wilkins**

NVIDIA's position as the main supplier of AI chips may be under threat from a specialised chip pioneered by Google, with reports suggesting companies like Meta and Anthropic are looking to spend billions on Google's tensor processing units.

What is a tensor processing unit?

The success of the artificial intelligence industry has been in large part based on graphical processing units (GPUs), a kind of computer chip that can perform many parallel calculations at the same time, rather than one after the other like the computer processing units (CPUs) that power most computers.

GPUs were originally developed to assist with computer graphics, as the name suggests, and gaming. "If I have a lot of pixels in a space and I need to do a rotation of this to calculate a new camera view, this is an operation that can be done in parallel, for many different pixels," says Francesco Conti at the University of Bologna in Italy.

This ability to do calculations in parallel happened to be useful for training and running AI models, which often use calculations involving vast grids of numbers performed at the same time, called matrix multiplication.

"GPUs are a very general architecture, but they are extremely suited to applications that show a high degree of parallelism," says Conti.

However, because they weren't originally designed with AI in mind, there can be inefficiencies in the ways that GPUs translate the calculations that are performed on the chips.

Tensor processing units (TPUs), which were originally developed by Google in the mid 2010s, are instead designed solely around matrix multiplication, says Conti.

This year, Google released the seventh generation of its TPU, called Ironwood, which powers many of the company's AI models like Gemini and the protein-modelling AlphaFold.

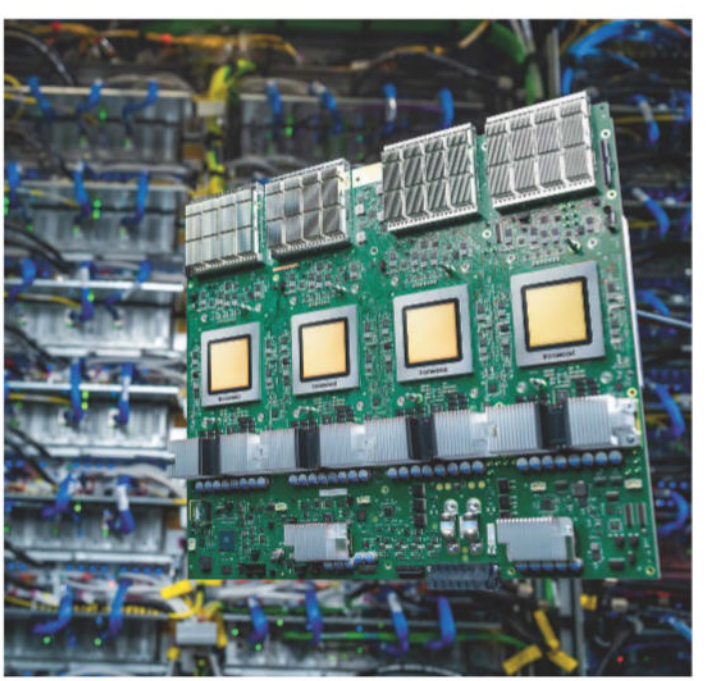
Are TPUs much better than GPUs for AI?

Technologically, TPUs are more of a subset of GPUs than an entirely different chip, says Simon McIntosh-Smith at the University of Bristol, UK. "They focus on the bits that GPUs do more specifically aimed at training and inference for AI, but actually they're in some ways more similar to GPUs than you might think." But because TPUs are designed with certain AI applications in mind, they can be much more efficient for these jobs and save potentially tens or hundreds of millions of dollars, he says.

However, this specialisation also has its disadvantages and can make TPUs inflexible if the AI models change significantly between generations, says Conti. "If you don't have the flexibility on your [TPU], you have to do [calculations] on the CPU of your node in the data centre, and this will slow you down immensely," says Conti.

"TPUs are designed with certain AI applications in mind, they can be much more efficient"

One advantage that Nvidia GPUs have traditionally held is that there is simple software available that can help AI designers run their code on Nvidia chips. This didn't exist in the same way for TPUs when they first came about, but the chips are now at a stage where they are more straightforward to use, says Conti. "With the TPU, you can now do the same [as GPUs]," he says. "Now that you have enabled that, it's clear that the availability becomes a major factor."



Ironwood is Google's latest tensor processing unit

GOOGLE

Who is building TPUs?

Although Google first launched the TPU, many of the largest AI companies (known as hyperscalers), as well as smaller start-ups, have now started developing their own specialised TPUs, including Amazon, which uses its own Trainium chips to train its AI models.

"Most of the hyperscalers have their own internal programmes, and that's partly because GPUs got so expensive because the demand was outstripping supply, and it might be cheaper to design and build your own," says McIntosh-Smith.

How will TPUs affect the AI industry?

Google has been developing its TPUs for over a decade, but it has mostly been using these chips for its own AI models. What appears to be changing now is that other large companies, like Meta and Anthropic, are making sizeable purchases of computing power from Google's TPUs.

"What we haven't heard about is big customers switching, and maybe that's what's starting to happen now," says McIntosh-Smith. "They've matured enough and there's enough of them."

As well as creating more choice for the large companies, it could make good financial sense for them to diversify, he says. "It might even be that that means you get a better deal from Nvidia in the future," he says.

Physics

Universal law for how objects shatter

Knowing how brittle objects fragment could improve mining and help prepare for rockfalls

Karmela Padavic-Callaghan

A DROPPED plate, broken spaghetti and a smashed drinking glass all seem to follow the same law of physics when it comes to how many fragments of a given size they will shatter into.

For several decades, researchers have known that there is something universal about the process of fragmentation, when an object breaks into many parts when dropped or smashed. If you made a graph of how many fragments existed at each possible size, it would have the same shape regardless of the object that shattered.

Emmanuel Villermaux at Aix-Marseille University in France has now derived an equation that explains that shape, effectively formulating a universal law for how objects break.

Instead of focusing on the details of how cracks appear in an object before it fragments, he took a more zoomed-out approach. Villermaux considered all possible sets of fragments that an object can shatter into and picked out the most probable set, the one with the highest entropy, which captured breakages that were messy and irregular. This is similar to the way many laws concerning large ensembles of particles were derived in the 19th century, he says.

> "Understanding fragmentation could alter how much energy is spent shattering ore in mining"

Additionally, he used a law of physics that describes changes in the total density of fragments when the object is shattering, which he and his colleagues had previously found.

Together, these two ingredients let him derive a simple equation predicting how many fragments of each size a breaking object should produce.

To see how well it worked, Villermaux compared it with a whole slew of past experiments with shattering glass bars, dry spaghetti, plates, ceramic tubes and even plastic fragments in the ocean and waves breaking on choppy seas. Across the board, the way fragmentation showed up in each of these scenarios followed his new law, capturing the ubiquitous graph shape that researchers had seen before (*Physical Review Letters*, doi.org/qf98).

The equation doesn't work in cases where there is no randomness and the fragmentation process is too regular, for example when a jet of liquid breaks up into many droplets of uniform size following deterministic laws of fluid physics, and in some cases where fragments interact with each other during shattering, he says.

Ferenc Kun at the University of Debrecen in Hungary says that because the graph shape that Villermaux's analysis explained is so ubiquitous, it isn't surprising that it stems from a bigger principle. At the same time, it is amazing how broadly it works and how it can be amended in some cases where there are additional constraints, such as in plastic where cracks can sometimes "heal", he says.

Fragmentation isn't just an interesting physics problem. Understanding it better could have real implications for how energy is spent on shattering ore in industrial mining, for example, or how we prepare for rockfalls that are increasingly happening in mountainous regions as global temperatures rise, says Kun.

Going forward, Kun says it may be interesting to consider the distribution of not only the sizes of fragments, but also their shapes. Additionally, it is an open question to determine what the smallest possible size of a fragment could be, says Villermaux. ▮

Animal behaviour

False thumb allows pandas to use tools to scratch that itch

GIANT pandas have been seen using twigs or pieces of bamboo to scratch themselves.

Other than an old anecdotal report about giant pandas rubbing dirt into their fur, this is the first recorded instance of tool use among these animals, says Bin Yang at the Shaanxi Institute of Zoology in China.

"Because pandas spend a lot of time eating and resting, they give the impression of being lazy, fond of food and cute," says Yang. "So, when we discovered that pandas can use tools, it changed our previous perspective about them."

Yang and his colleagues had noticed this behaviour during other work and set out to learn more about it. They recorded 383 instances of tool use over 50 days of observation of 18 captive giant pandas (*Ailuropoda melanoleuca*) in a zoo in China, including both males and females.

The pandas mostly used twigs or pieces of bamboo they broke off trees, and almost always to scratch (*Current Biology*, doi.org/qgbc). This meant they could scratch parts of the body that would be hard to reach without the tools.

Since the giant pandas at this zoo live in a naturalistic outdoor setting, Yang says wild pandas may also use tools in this way, although no observations of wild pandas doing this have yet been reported.

PANTHER MEDIA GLOBAL/ALAMY

Bamboo can make for a tasty meal– and an effective back scratcher

Unlike other bears, pandas have a "false thumb" on their paws, a sixth digit much shorter than human thumbs that allows them to grasp objects in a way that other bears can't.

Pandas have relatively large brains – the breaking off of sticks specifically to use as tools suggests a capacity for short-term planning, the researchers say.

"Pandas might have more complex cognition and behaviours than previously thought," says Yang, but more work would be needed to learn more about this behaviour, including whether they can be directed to use tools. ▮

Joshua Rapp Learn

Health

Monthly injection could replace daily steroids for asthma

Carissa Wong

SOME people with severe asthma rely on daily steroid pills, which raise the risk of diabetes, infections and bone problems. Now, a study backs the idea that a monthly antibody injection is a safer alternative.

Asthma is usually managed with an inhaler, but in severe cases it can also be treated using steroid pills. These lower inflammation in the airways and reduce symptoms and the risk of asthma attacks, but come with severe side effects. "We'd like to get people off oral steroids as much as possible," says Fan Chung at Imperial College London, who wasn't involved in the study.

Prior trials have shown that tezepelumab, a monthly antibody injection, reduces symptoms of severe asthma better than a placebo injection. This has led to its approval in dozens of countries, including the UK and US, over the past few years. But it was unclear whether the drug could reduce, or even eliminate, the need for steroid pills.

To explore this, David Jackson at Guy's and St Thomas' hospital in London and his colleagues recruited 298 people with severe asthma, aged between 18 and 80, from 11 countries. The participants, who were taking daily inhalers and steroid pills, were asked to also take tezepelumab for one year.

The researchers found that the participants' oral steroid doses could be gradually reduced over the course of the study, under the supervision of their doctors (*The Lancet Respiratory Medicine*, doi.org/qf9v).

By the end of the year, about half no longer required any steroid pills, and 40 per cent of them were able to lower their dosage to a level where "the side effects are going to be minimal", says Chung. "It's a very successful outcome," he says. "The trial confirms that tezepelumab is a useful treatment for severe asthma patients, reducing their need for daily pills."

Archaeology

Rapa Nui statues may have been built by small groups

James Woodford

JON ARNOLD IMAGES LTD/GAVIN HELLIER/ALAMY

The giant moai may not have been built by a central authority

RAPA NUI's monumental stone statues may have been created through a decentralised artistic and spiritual tradition, with different communities making their own carved stone giants, rather than a unified effort coordinated by powerful rulers. That is the finding of an attempt to definitively map the island's main stone quarry.

Also known as Easter Island, Rapa Nui in the Pacific Ocean is thought to have been inhabited by Polynesian seafarers since around AD 1200.

Archaeological evidence suggests that the Rapa Nui people weren't politically unified, but there is debate over whether the hundreds of stone statues known as moai were coordinated by a centralised authority.

The island had only one quarry supplying the rock from which the statues were carved, a site called Rano Raraku.

Carl Lipo at Binghamton University in New York and his colleagues used drones and high-tech mapping equipment to create the first 3D map of the quarry, which contains many unfinished moai. Previous studies have come to varying conclusions about the number of moai that remain in the quarry, says Lipo.

The team recorded 426 features representing moai at various stages of completion,

30

Separate work areas found in the Rano Raraku quarry

341 trenches cut to outline blocks for carving, 133 quarried voids where statues were successfully removed, and five bollards that probably served as anchor points for lowering moai down slopes (*PLoS One*, doi.org/hbcrzw).

They also found the quarry was divided into 30 work areas that each appeared to be separate from the others and featured different carving techniques, says Lipo.

Combined with previous evidence showing that small crews could have moved the moai, and that groups marked out separate territories at freshwater sources, Lipo says it appears the statue carving wasn't the result of a centralised political authority.

"The monumentality represents competitive display between peer communities rather than top-down mobilisation," he says.

There has been debate among historians about the supposed decline of the Rapa Nui people, with some claiming that overexploitation of resources led to a societal collapse.

Lipo says the collapse story assumes centralised leaders drove the construction of the monuments and this led to deforestation and societal failure. "But if monumentality were decentralised, and that emerged from community-level competition rather than chiefly aggrandisement, then the island's deforestation could not be blamed on megalomaniacal leadership," he says.

However, other researchers aren't so sure. Dale Simpson at the University of Illinois Urbana-Champaign agrees there wasn't one overarching chief like there was in other Polynesian cultures such as in Hawaii or Tonga. But, he says, the clans weren't as separate and decentralised as Lipo and his colleagues have proposed, and there must have been collaboration between groups.

Jo Anne Van Tilburg at the University of California, Los Angeles, says further research is underway to clarify how Rano Raraku was used, and Lipo's team's conclusions are "premature and overstated".

Humans

Taxable crops led to the first states

How the first large-scale societies formed has long been debated, but the answer could lie in the farming of easily taxed plants like wheat and maize, finds **Chris Simms**

THE cultivation of cereal grains probably led to the emergence of the first states – which operated mafia-like protection rackets – and to the adoption of writing for the purposes of recording taxes.

There is wide debate over how the first large societies emerged. Some see agriculture as the root of civilisation, while others see it as an invention born of necessity when the traditional hunter-gathering life became untenable. But many propose that the intensification of agriculture provided a surplus that could be stored and taxed, and that this enabled the formation of states.

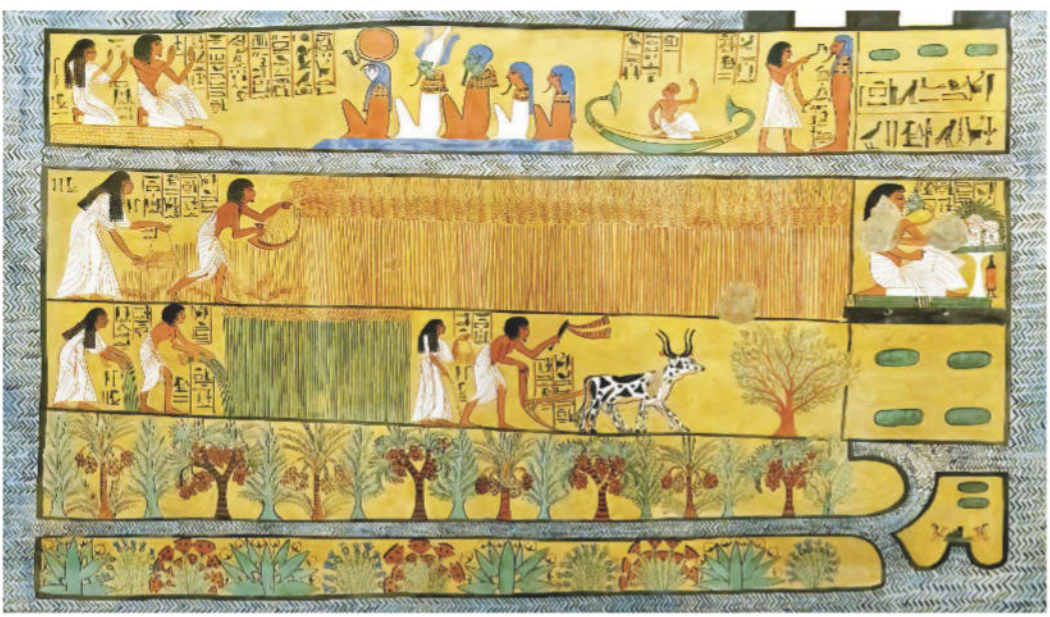
"By using fertilisation and irrigation, [early farming societies] could hugely increase the output and, therefore, there was this surplus that was available for the construction of the state," says Kit Opie at the University of Bristol, UK.

However, the timeline for these developments doesn't quite match up. Our first evidence of agriculture is from about 9000 years ago, and it was invented at least 11 times on four continents. But large-scale societies didn't emerge until about 4000 years later, first in Mesopotamia, then in Egypt, China and Mesoamerica.

To look for more evidence, Opie and Quentin Atkinson at the University of Auckland in New Zealand turned to a set of family trees mapping out the evolution of the world's languages, representing the relationships between cultures, and borrowed statistical methods from phylogenetics, the study of evolutionary relationships.

The pair used the language data in conjunction with information from anthropological databases on hundreds of pre-industrial societies to assess the probability that events such as the emergence of a state, taxation, writing, intense agriculture and the cultivation of cereal grains emerged in a specific order.

PEREGRINE/ALAMY



The ancient Egyptians cultivated cereal crops along the Nile

They found that intensive agriculture was coupled with the emergence of states, but the relationship wasn't simple. "It looked more likely that it was the states causing the intensification, rather than the intensification causing the states," says Opie.

"It makes sense that once you've got a state with money and people at its disposal, it can start doing irrigation," he says.

But the pair also found that states were very unlikely to emerge in societies that didn't have widespread production of cereal grains such as wheat, barley, rice and maize, whereas they were very likely to emerge in those with cereal grains as their main crop.

The results show that grain production and taxation were often associated, and taxation was less likely to arise in societies without grain (*Nature Human Behaviour*, doi.org/hbcnx4).

This is because cereal grains have great taxable potential, says Opie. They can be easily assessed because they are grown in fixed fields above ground, ripen at predictable times and can be stored for long periods. "Root crops like cassava or potatoes were hopeless for taxation," he says. "The argument is that states, or protection rackets, would defend these fields from external states in exchange for tax."

"The argument is that states would defend these fields from others in exchange for tax"

When it came to writing, Opie and Atkinson found that the practice was very unlikely to be adopted in societies without a tax system but very likely in those that did have one. Opie suggests that writing was invented and adopted to record those taxes.

The results also indicate that, once formed, states were more likely to stop producing non-grain crops than non-states. "I would argue that we find strong evidence that they actually got rid of roots, tubers and fruit trees so that all the possible fields could be used for grain because none of the other things were good for taxation," says Opie. "People were forced into using these kinds of crops, and it had a bad effect on us."

Although the move towards cereal cultivation was linked with a population boost in the Neolithic period, it also led to a fall in overall health, height and dental health.

"Applying phylogenetic methods to cultural evolution is innovative, but it may oversimplify the complexity of human history," says Laura Dietrich at the Austrian Archaeological Institute in Vienna. Archaeological evidence shows that in south-west Asia, intensified agriculture in prehistoric times culminated in sustained state formation, whereas in Europe it didn't, she says. ▮

Neuroscience

Your brain undergoes four dramatic periods of change from age 0 to 90

Carissa Wong

OUR brain function is far from static throughout our lives. We already know that our capacity to learn, and our risk of cognitive decline, varies as we age. Now, scientists may have uncovered a reason why: our brain wiring seems to undergo major turning points around the ages of 9, 32, 66 and 83.

The brain has distinct regions that exchange information via white matter tracts – structures made of spindly projections called axons that project from neurons. These connections influence our cognition. But it was unknown whether major shifts in this wiring occur throughout life.

To find out, Alexa Mousley at the University of Cambridge and her colleagues analysed MRI brain scans from around 3800 people in the UK and US, who were mostly white and ranged in age from newborns to 90. The researchers found that among people who reach 90, the brain's wiring has generally undergone five main phases, separated by four turning points (*Nature Communications*, doi.org/hbcnbx).

In the first phase, which occurs between birth and around 9 years old, white matter tracts between brain regions seem to become longer or more convoluted, making them less efficient. "It takes longer for information to pass between regions," says Mousley.

"As we grow and experience things, the brain connections we don't use are pruned away"

This could be because our brain is packed with lots of connections as infants, but as we grow and experience things, the ones we don't use are pruned away. The brain seems to prioritise making a broad range of connections that are useful for things like learning to play the piano, at the cost of being less efficient, says Mousley.

But during the second phase, roughly between 9 and 32 years old, this pattern seems to flip, which may be driven by the onset of puberty and its hormonal changes influencing brain development, says Mousley. "Suddenly, the brain is increasing the efficiency of the connections." This may support the development of skills like planning and decision-making, and improvements in cognitive performance, such as working memory, says Mousley.

The next phase is the longest, spanning from 32 until 66. In this phase, your brain is still changing, but much less, says Mousley. Specifically, connections between brain regions switch back to gradually losing efficiency, she says. "It's unclear exactly what drives this shift, but the 30s map onto a lot of different major lifestyle changes – for instance, having kids – so that could play a role," says Mousley. It could also just be down to general wear and tear of the body, says Katya Rubia at King's College London.

From age 66 to 83, the team found that connections between neurons in the same brain region seem to be more stable than between those in distinct areas.

In the final phase, from age 83 to 90, connections between brain regions weaken and increasingly pass through "hubs" that connect lots of areas. "It suggests that there are fewer resources to maintain connections during this phase, so the brain relies more on using certain regions to act as hubs for connections," says Mousley.

Understanding the normal turning points will help us find out what deviates during neurodegenerative or mental health conditions, says Rubia. "Once you understand what's deviating, that can help you pinpoint ways to treat it." ▮

Animal behaviour

Deadly fungus makes sick frogs jump further

AN ONGOING global pandemic of deadly chytrid fungus is plaguing amphibians. But in one threatened Australian frog species, the infection has an unusual side effect: huge hops.

Verreaux's alpine tree frogs (*Litoria verreauxii alpina*) that are infected with chytrid fungus, also known as *Batrachochytrium dendrobatidis* or Bd infections, can jump nearly a quarter further than their uninfected counterparts.

"[The findings] remind you how resilient these amphibians are and how they are dealing with the bombardment of this really horrible pathogen. And yet, their bodies are able to do something miraculously unexpected," says Taegan McMahon at Connecticut College in New London, who wasn't involved in the research.

Alexander Wendt at the University of Melbourne in Australia and his colleagues were studying how Bd infections affect the health of alpine tree frogs, using their athletic performance as a proxy for physiological effects.

In the lab, the researchers divided 60 frogs into uninfected and Bd-infected groups. Wendt and his colleagues tested how the frogs responded to temperature extremes and how far they jumped when gently prodded.

Surprisingly, by the sixth week post-infection, infected frogs leapt nearly 24 per cent further than uninfected frogs (*Animal Conservation*, doi.org/qf9h). In most other amphibians, their immune system's focus on fighting the fungus drains the animals' energy.

ROBERT VALENTIC/NATUREPL.COM

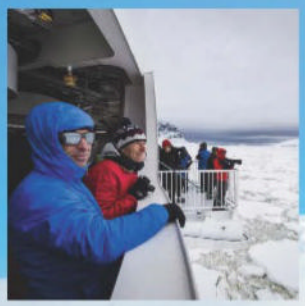
Verreaux's alpine tree frogs are threatened by the chytrid fungus

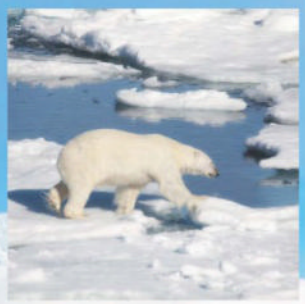
The alpine tree frogs don't appear to have a strong immune response to Bd to slow them down, and the boost to their bounce may be an adaptation for speedily finding a mate for one last chance to reproduce before the infection turns for the worse. Other frog species are known to increase their calling to mates when infected with Bd.

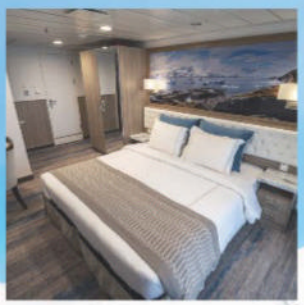
A brief supercharge in jumping prowess may work to Bd's benefit too. "Evolutionarily, it would make sense for [Bd] to facilitate movement so that it's getting a higher level of transmission and more longevity in a host," says McMahon. ▮

Jake Buehler

New Scientist Discovery Tours







Arctic expedition cruise with Dr Russell Arnott: Svalbard, Norway

17 June 2026 | 12 days

Explore the northernmost region of Earth, the realm of the polar bear and the midnight sun, whilst travelling aboard the Greg Mortimer which is at the cutting edge of nautical technology. This cruise will be a truly enriching trip of a lifetime.

Enjoy a full programme of talks, shore visits and Zodiac boat safaris covering topics including glaciology, botany, marine biology, astronomy and the history of polar exploration, deepening your connection to this remote and rugged archipelago. Accompanied by Dr Russell Arnott and speakers from *New Scientist*, along with the highly knowledgeable and supportive expedition team, experts in exploration, science and wildlife.

Witness polar bears on substantial ice flows (June is one of the best months to spot them) as well as a plethora of other wildlife species on land, sea and in the air. June is when Minke, humpback and fin whales arrive back to the Arctic having spent the winter in warmer tropical waters. During this time, the tundra and hillsides are in bloom as the ice melts away and endemic flowers begin to blossom. The towering cliffs and dramatic mountain ranges are teeming with millions of sea birds laying their eggs.

Explore the Arctic town of Longyearbyen, the world's northernmost settlement, situated in a valley on the shores of the idyllic Adventfjord, surrounded by steep mountains and several glaciers.

This unique cruise will be hosted aboard a new state-of-the-art polar expedition vessel, the Greg Mortimer, the first passenger ship to feature the revolutionary Ulstein X-BOW® allowing a sleeker cruising experience and reducing fuel consumption. You will experience the majesty of Norway's Svalbard with its ancient glaciers, glass-still fjords, imposing pack ice and distinct landscape where wildlife thrives at nearly 80° north. With no more than 128 guests, amazing viewing space and a ship-build designed to minimise negative environmental impacts, the Greg Mortimer guarantees a far more enjoyable guest experience than the other older and larger expedition ships.

Travel with like-minded people, who love to connect with the natural world and the wonder of science. An ideal environment for curious-minded couples, friends and solo travellers to relax.

Highlights include:

- Venture close to 80° north, searching for polar bears on pack ice.
- Fascinating talks from marine biologist Dr Russell Arnott plus *New Scientist* contributors and expedition crew.
- Discover the thrill of seeing species such as walrus, seals, whales, reindeer, arctic fox, guillemots and puffins.
- Cruise along blue glacier fronts and through stunning fjords on a purpose-built intimate powlar expedition ship.
- Enjoy tundra hikes amid stunningly beautiful scenery.
- Daily Zodiac boat safaris exploring fjords and glaciers.

Watch the video of this year's cruise at
newscientist.com/arctic

Views

Comment

Who's a good boy?

Our increasing tendency to treat pets as surrogate children, or "fur babies", has dire consequences for these animals, warns **Eddie Clutton**

ADRIÀ VOLTÀ

WHERE once they lived in our backyards, many pets – for better and for worse – have now transitioned to a pampered life as "fur baby" family members. The American Veterinary Medical Association recently highlighted that pet owners were projected to spend nearly $1 billion on costumes for their pets this year. Many see this as harmless fun, but the increasing tendency to treat pets as surrogate children – or at least small humans – can have severe health and welfare consequences for the animals involved.

The forerunners of the modern fur baby belonged to a widely distributed population of small, domesticated carnivores of the genera *Canis* and *Felis*. Despite being relatively short-lived, such pets usually brought considerable pleasure, companionship and some health benefits to their human owners, while teaching children a respect for, and the vital requirements of, these animals.

Pets have also brought other educational gains, such as the opportunity to experience and grieve non-human death in preparation for the demise of human loved ones. Most pets would be rewarded for this with food, water, shelter, vaccines, flea powders and a name reflecting their service (Fido), colour (Sooty) or behavioural traits (Rover). Importantly, they were usually assured a relatively pleasant death before the inevitable effects of advanced age extinguished any remaining quality of life.

The pet-to-fur-baby evolution can be attributed to many things, including undue emphasis on the human-animal bond, increasing affluence, ignorance of animals' biological needs, irresistible consumerism – and, in propagating ill-advised (though well-intentioned) anthropomorphism, social media. The principal causes, drivers and outcomes of fur babyism have intensified and spread globally. Evidence for this is inescapable and goes beyond the availability of clothes for birthdays, Halloween or Christmas. Strollers, jewellery, fragrances, nappies, nail polish, coat dyes, birthday cakes and shoes are now available for the modern fur baby, as are "gold standard" veterinary treatments.

The adverse physical and psychological health effects of fur babyism are well documented. Take strollers for dogs: while potentially useful for injured or arthritic animals, their excessive use in other dogs can lead to muscle wastage, joint damage and obesity. Restricting the fur baby's movement limits its natural inclination to explore, mark territory and interact with environmental features, such as others of its species, leading to fear and anxiety.

Given these potential health and welfare hazards, one would expect the veterinary profession to adopt a universally condemnatory position with respect to the fur baby phenomenon. Oddly, this isn't the case, with attitudes ranging from censure to capitalisation. The latter position is troubling because in encouraging overtreatment, for example radiotherapy in geriatric animals, it may further compromise animal welfare without necessarily improving animal health.

An owner's profound love for their pet can always be accepted, provided the animal's interests are prioritised, which includes ensuring them freedom from pain, suffering and distress. What is considerably less defensible is the vet who cashes in on an owner's misguided love for their pet to conduct unnecessary, invasive, painful, unproven and expensive tests and procedures on an animal that cannot give its consent.

All caregivers should reflect on the suffering that may arise when animals are treated inappropriately: that is, as children rather than dogs or cats. And vets pandering to the fur baby trend should know better. ▮

Eddie Clutton is co-author of *Veterinary Controversies and Ethical Dilemmas* (Routledge)

The neuroscience column

Diving in

Diving in Researchers are finding that cold-water swimming may reshape our brains for the better in lasting ways, and could even protect against some age-related conditions, says **Helen Thomson**

Helen Thomson was previously head of features at *New Scientist*, and specialises in life sciences, health and biotech. She is the author of books including *Unthinkable: An extraordinary journey through the world's strangest brains* and *This Book Could Fix Your Life*.

Swimming in water below 15°C (59°F) should always be done with a partner, a float, a bright hat and a full understanding of the potential risks and how to mitigate them. For more on water safety for cold-water swimming, the Royal National Lifeboat Institution has resources available online.

IT IS 8am and I am standing at the edge of my local lake at Beckenham Place Park in London, the early morning sun just beginning to peek over the trees. A layer of mist is rising from the cold water and all is still – not even the ducks are braving a dip today. My friend and I, however, are standing in our bathing suits despite the water temperature sitting in single digits. The first step into the water always takes my breath away, but as my body acclimatises and we swim a wide loop, I feel like a new person.

Over the past few years, I have converted more than a few friends into cold-water devotees. My pitch is simple: nothing lifts your mental health quite like it. Until recently, my case was mostly anecdotal. But as more people are becoming enthused by ice baths, cold showers and winter swims, researchers are beginning to uncover exactly what these freezing plunges do to our brain chemistry. And as it turns out, my weekly dips may be reshaping my brain in lasting ways.

I am not alone in loving cold swimming – around 6.8 million people in England regularly swim outdoors. That is hardly surprising, since there is now solid evidence suggesting regular cold-water immersion reduces fatigue, lessens symptoms of depression and improves well-being.

For instance, in one study, 36 people who completed a four-month programme of open-water swimming for four days a week over winter showed significantly lower tension and fatigue compared with a group of non-swimmers. The swimming group also saw increased vigour, better memory and improved mood.

Cold exposure acts on multiple physiological pathways, including the heart and immune system, and regular winter swimmers are known to have improved immune health, experiencing fewer colds and reduced risk of cardiovascular disease. But it is the neurological effects that I find most intriguing.

For instance, the effect on your mood may be because exposing your semi-naked body to freezing water triggers an acute stress response: your brain orchestrates a sudden spike in adrenaline, dopamine and cortisol – a cocktail of chemicals that gives you a similar high to the one you get after exercising.

Evolutionarily, this is a clever survival strategy. Exposure to extreme cold is life-threatening, so this "cold-shock response" delivers a burst of energy, increases alertness, reduces pain and mobilises your stress response to help you escape danger.

> **"There is now solid evidence suggesting regular cold-water plunges reduce fatigue and improve well-being"**

It is also the reason that people can get into trouble swimming in cold water. Without taking proper precautions, it can make you inhale sharply, affect movement and cause heart attacks in rare cases. However, deliberately triggering this response in the modern-day setting of a quiet lake, watched over by lifeguards, and having had the right training gives me access to its benefits without as much danger. Deficits in those same chemicals play a critical role in conditons such as depression and anxiety, so artificially boosting them may explain why mood is temporarily lifted after a swim.

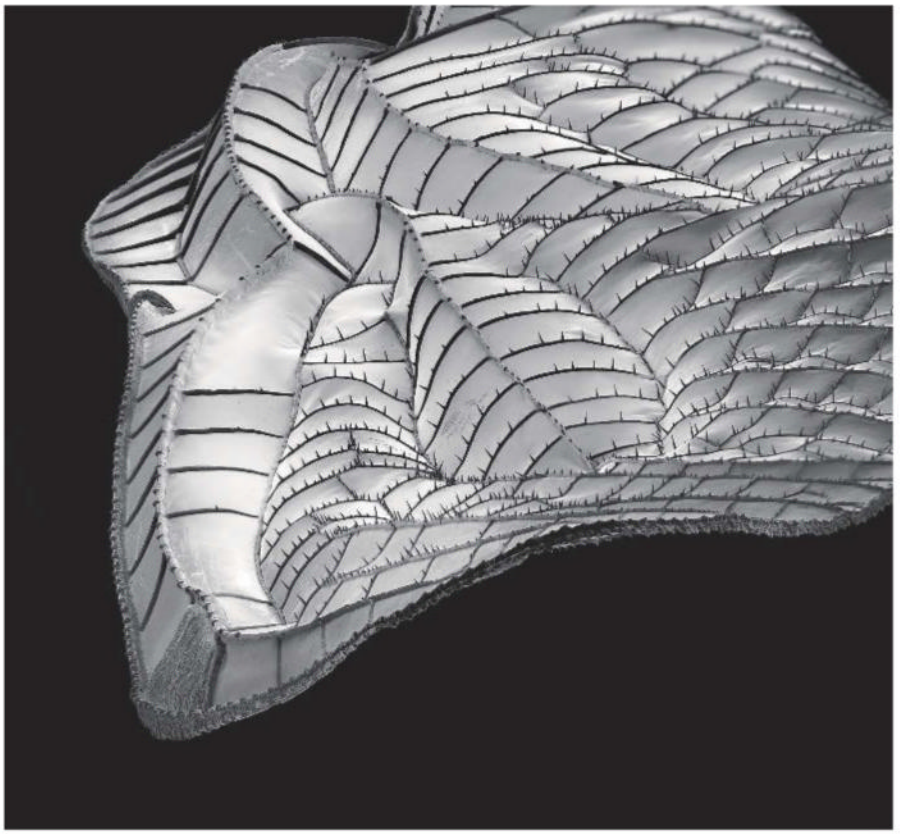
Our cold-shock response also releases proteins, such as RNA-binding motif protein 3, which supports the repair of synapses – the connections between neurons. In mice predisposed to develop a version of Alzheimer's disease, increased levels of this protein protected them from neurological damage, leading some researchers to speculate that regular cold-water swimming may have long-term neuroprotective effects in humans, too – although this hasn't yet been studied directly.

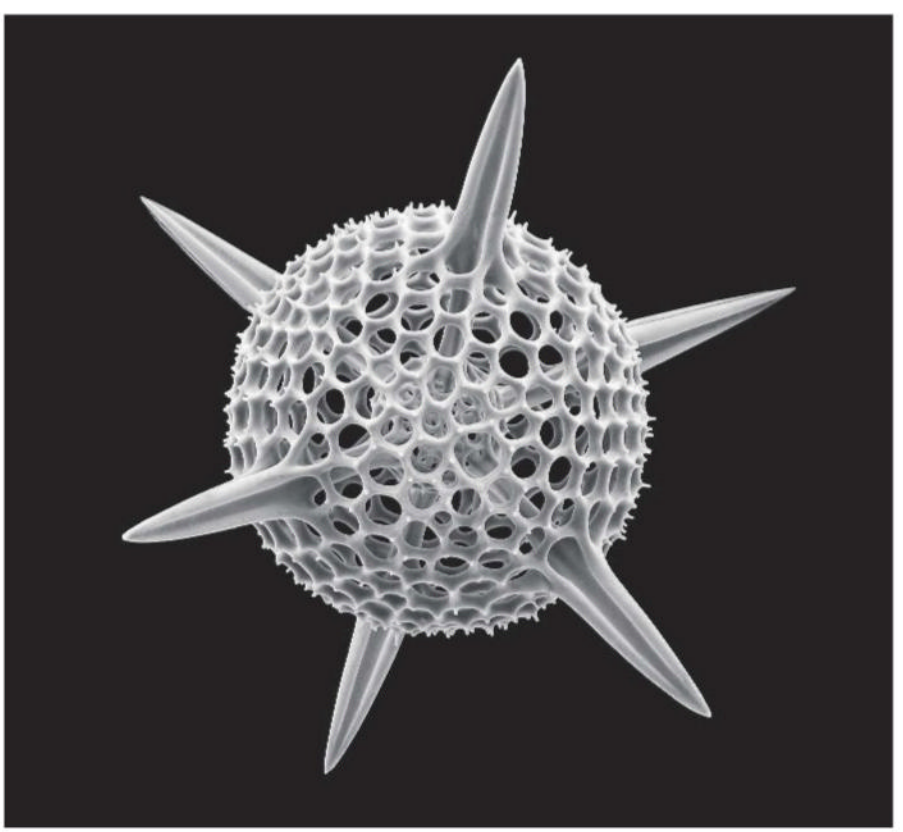
Excitingly, researchers are even starting to directly examine the effects of cold-water swimming on the brain. Ala Yankouskaya at Bournemouth University in Poole, UK, and her colleagues scanned the brains of 33 people who don't normally swim in cold water before and after a 5-minute whole-body bath in 20°C (68°F) water. It was the first time researchers had captured real-time information about how brain networks interact following cold-water exposure.

They discovered beneficial shifts in the connectivity between several brain regions, particularly the medial prefrontal cortex and the parietal lobe – areas associated with emotional control, attention and decision-making. Activity in these areas is often disrupted in people with depression and anxiety, which may explain why cold-water swimming can act as a therapeutic tool.

Of course, it isn't all clarity and euphoria. There have been some rare cases of transient memory loss associated with cold-water swimming, typically in older adults, and it isn't clear why. Hypothermia is another risk factor if you stay in too long. Still, I am heartened that the clear-headedness and improved mood I feel after my dips are gaining some scientific support. If I can keep it up, they may even protect me from some age-related conditions. ▮

Up next week: Annalee Newitz





Zooming in

Photographer Michael Benson Abrams

A BUTTERFLY net, tweezers and a drawstring bag brimming with small plastic vials: it is an unusual toolkit for a photographer, but not for Michael Benson.

Over six years, he gathered specimens for his new book *Nanocosmos: Journeys in electron space*, a collection of images depicting the microscopic world in remarkable detail. "I'm fascinated by the frontier between what we know and what we don't – a zone typically associated with science," he says. "But I go there as an artist, not as a scientist."

Still, that hasn't stopped Benson from utilising gear often reserved for physicists and biologists. He produced every image in *Nanocosmos* with scanning electron microscopes (SEMs), which emit a focused beam of electrons to map the contours of a surface in astonishing detail. The resulting images capture his submillimetre subjects with such clarity that they almost seem as if they are from an alien planet.

Consider this Asilidae robber fly (far left) next to a plant from Alberta, Canada. The two together are only slightly wider than 1 centimetre across. But thanks to SEM technology, we can see nearly every hair on the fly's body, each claw on its legs and even some of the thousand of receptors that make up its bulbous eyes.

Near-right, top, is Benson's image of a wing of the eastern pondhawk dragonfly (*Erythemis simplicicollis*), viewed from the wingtip down. The wing is about 3 millimetres wide. Below is Benson's shot of a single-celled marine organism (*Hexalonche philosophic*) from the equatorial Pacific that, tip-to-tip, measures 0.2 millimetres.

Grace Wade

The look of success

What were the best sci-fi shows of 2025? *Andor* and *Severance* are still up there, but **Bethan Ackerley** also has some unexpected tips to share

CATACLYSMS, conspiracies and rebellions featured in many of 2025's biggest sci-fi shows. And while all that instability reflects poorly on the state of our world, at least it did make for fantastic television. Here are six series that should be on your to-watch list.

Two of the year's best shows took their time to return for fresh seasons. When *Andor* (Disney+) first aired in 2022, it didn't quite feel real. A *Star Wars* show that was as enjoyable for newbies as it was for seasoned fans? A prequel about Rebel Alliance spy Cassian Andor, written and performed with the kind of fervour usually reserved for Shakespeare? And it is actually good? You are having me on, I thought at the time.

But it really is brilliant. And somehow the second and final (sob) season of *Andor* is even better than the first. Now committed to fighting the Galactic Empire, Cassian steals ships and rescues operatives at the behest of the shadowy spymaster Luthen – but something bigger is on the horizon. Timely in our authoritarian era, hard-edged and beautifully written, *Andor* was undeniably the best show of this year.

The other laggard, also from 2022, was *Severance* (Apple TV), featuring a very different group of rebels. Set at the mysterious Lumon Industries, it follows a group of employees who have chosen to be "severed": their memories of work have been separated from the rest of their consciousness, effectively creating another person, known as an "innie", who has never known the light of the sun.

The parlous life of an innie means being terrorised in countless ways by Lumon middle managers, while the "outtie" who put them in this hellhole remains blissfully ignorant. Their only recourse? Death by resignation. Season two takes the innies in some terrifying directions, revealing more of the strange workings of Lumon. *Severance* is a satisfying mystery that is smart enough to burn through plotlines and actually answer your questions, even if it then supplies you with more.

WARNER BROS. DISCOVERY; BELOW: DISNEY/BRIAN ROEDEL

In *Common Side Effects*, Marshall makes a key discovery; Below: James Marsden as President Cal Bradford in *Paradise*

"Instability featuring in many of 2025's sci-fi shows reflects badly on our world, but did make for fantastic TV"

Here's a show that might not seem like a *New Scientist* pick: *Paradise* (Disney+/Hulu), which was an overnight hit back in January. It starts off as a pedestrian political thriller, albeit one with the good sense to cast Sterling K. Brown as Xavier Collins, a US Secret Service agent, and James Marsden as Cal Bradford, the president Collins is suspected of murdering. Their chemistry is terrific, the machinations frenetic.

It should have been a fun but forgettable binge-watch, but a sci-fi twist, which comes at the end of one of the finest first episodes I have seen in years, lifts *Paradise* from the merely entertaining to the gripping. No spoilers here, but it casts a chilling pall over the investigation and keeps things from getting too silly. Because it is silly – many key moments are set to waifish covers of 1980s power ballads – but to just the right degree.

Every year, the world ends a thousand times on television, but some apocalypses are better than others. One of 2025's best was *The Eternaut* (Netflix), which brought the classic sci-fi comic by Héctor Germán Oesterheld into the present day.

After a deadly snowfall hits Buenos Aires, former soldier Juan Salvo dons a gas mask and waders to head into the streets, searching for his family. It soon becomes clear that the snow is just the start: Juan and a few other survivors must piece together what exactly has happened and how to stop it.

Steeped in the real-life history of the military dictatorship of Argentina in the late 1970s, and of Oesterheld's murder at its hands, *The Eternaut* approaches its source material with the respect it deserves. This chilling series contains one of my favourite scenes of the year – a claustrophobic sequence in which huddled survivors in an apartment complex realise that Juan's clothes let him survive outside, so they must take them from him.

If you prefer your dystopias on the warmer side, try *Pluribus* (Apple TV), the new series from *Breaking Bad* creator Vince Gilligan, set in the sunny climes of New Mexico. Its hero, jaded romance novelist Carol Sturka, isn't much of a hero at all – especially once most of humanity is struck down by sudden-onset

happiness. They are all keen to serve Carol, one of the few to remain unaffected, in whatever way she wishes. And if they find out how to fix whatever makes her different, all the better.

Suppose there was a utopia and not everyone got to enjoy it? Carol wants no part of this mandatory love-in, but finding out how to get things back to normal will be tricky – not least because there is plenty to like about a world with no war or selfishness.

Pluribus is achingly self-assured, taking you in directions you don't expect, all anchored by a fantastic central performance.

Surprises in store

On the subject of happiness, let's end on something lighter. *Common Side Effects* (Channel 4/Cartoon Network) is the show that surprised me most this year, not because it was good – which was all but guaranteed thanks to the involvement of Joe Bennett, co-creator of the excellent *Scavengers Reign* – but because it has attracted a big enough audience to be renewed for a second season.

In this animated series, fungi expert Marshall makes a remarkable discovery: a mushroom that appears to cure all illnesses and injuries. Naturally, the Blue Angel, as it is known, is a hot commodity that must be kept from the hands of Reutical Pharmaceutical – the firm that, unbeknownst to Marshall, employs Frances, his childhood friend, with whom he has just reconnected.

Soon, a host of foes are on his tail – but this isn't just a conspiracy thriller or a tirade against big pharma. *Common Side Effects* is a thoughtful, funny show about building a better world. Let's try to follow its example in 2026. ▮

Humans and other animals

From animal rivals to Jane Goodall's last thoughts, here's **Bethan Ackerley's** guide to 2025's best science documentaries

Human (BBC iPlayer/NOVA)

Ella al-Shamahi is the perfect guide to our ancient ancestors. In *Human*, she takes us on a whistle-stop tour of our past over a span of 300,000 years, including our turbulent relations with other hominins.

The palaeoanthropologist builds a complex story in which we aren't the only ones with intelligence and creativity.

Highlights include a trip to Indonesia to see the remains of "hobbits" (*Homo floresienses*, our extinct metre-tall cousin), and some tiny shells ancient humans made into jewellery.

The series includes fascinating analyses of footprints in a dried-out lake, hinting at a mother's hurried journey, and growth lines in Neanderthal teeth, suggesting longer childhoods than we thought.

Once Upon a Time in Space (BBC iPlayer)

The latest project from James Bleumer is a must-watch series, covering the history of space exploration from the late 1970s to now. It shares many personal anecdotes, such as NASA astronaut Anna Fisher (pictured) revealing the hate hurled at her as the first

mother in space, and Michael Foale's firsthand account of how the crew of the Russian space station Mir survived after a collision that caused the station to depressurise.

We also see Carl McNair watch footage of his father discussing how proud he was of Ronald, his brother and Carl's uncle – one of the first Black astronauts, who died in the 1986 Challenger disaster. "From slavery to space in four generations," says Carl, overcome with joy and grief.

Kingdom (BBC iPlayer, airs on PBS from 24 January 2026)

Even before airing, the latest gem from David Attenborough and the BBC Natural History Unit was aptly described as the *Game of Thrones* of nature documentaries. The series is a blood-soaked, Shakespearean drama that will devastate you within its first episode. It follows four factions – a family of leopards, a wild dog pack, a

pride of lions and a hyena clan – in Zambia's Nsefu, a luscious tract of South Luangwa National Park.

Our story begins with the arrival of wild dog Storm and her crew and a skirmish with the elegant leopard Olimba. Things escalate as the rivals jostle for food and space, and shocking violence ensues.

That said, witnessing these lives is a privilege and you are sure to fall in love with them, especially the various family matriarchs and Flint, a three-legged wild dog who was caught in a poacher's trap. It's heart-in-mouth stuff. Have some tissues on hand.

Famous Last Words: Dr Jane Goodall (Netflix)

Legendary primatologist Jane Goodall sadly died earlier this year. But she is among the influential figures interviewed about their lives for *Famous*

***Last Words*, a new Netflix series adapted from a Danish format – to be released after its subjects' deaths.**

Fittingly for a scientific trailblazer, Goodall's interview is the first to be released, and she is on sparkling form throughout. She arrives clutching Mr H, a cuddly monkey, and sits down with a glass of whisky – medicinal, she stresses, to stop her voice tiring during the long conversation ahead.

The rest of the episode is just as charming. And, thankfully for us all, Goodall's voice never faltered: she kept on fighting for a kinder, more sustainable world right till the end. The interview touches on a host of topics, including her groundbreaking research, Shakespeare, animal grief, the supernatural, why she should never have got married, and the backstory of Mr H. But it is her warmth and wry humour that really makes this conversation so moving.

BBC/BBC STUDIOS; BBC/KEO FILMS/NASA; BBC STUDIOS/ANNA PLACE; STUART CLARKE/SHUTTERSTOCK

In search of the soul of 2025

It's been an eclectic year of sci-fi films, and **Simon Ings** finds that while many of them retrod old ground, a few set themselves apart where it counts

SOME ideas are so compelling, so intuitive, one would sooner recycle them than take them apart to explore. So, in 1950, Isaac Asimov fixed up some puzzle stories into a fiendish, Agatha Christie-in-space sci-fi novel, *I, Robot,* while in 1968, Stanley Kubrick's *2001: A Space Odyssey* set a high bar for films about (or at least containing) artificial intelligence. There, ideas-wise, the story of robots in cinema pretty much starts to repeat on an endless loop.

This year, *The Electric State* spun a yarn about a robot rebellion, *M3gan 2.0* showed you can't keep a good killerbot down and *Companion* took the femmebot's point of view to give us a decent adult-themed Asimov pastiche.

All three toyed with the usual notions around free will and indulged in handwringing about when to treat a machine like a person. I suspect Gerard Johnstone's *M3gan 2.0* was the most fun to work on, as 2023's rubber-boned robot babysitter returns from the dead (well, the back-up disc) to save the world from older-sister killbot Am3lia. The screenplay is a mess, but the gags, genre call-backs and jump scares are justification enough.

Drew Hancock's *Companion*, about a clueless femmebot discovering her true nature, looked like it would cut a little deeper, only to lose its nerve. Nine months after my review, all I recall is a wonderfully meat-headed cameo from Rupert Friend.

Anthony and Joe Russo's *The Electric State* got a widespread panning, not least because the duo's make-it-up-as-we-go style was so painfully ill-suited to the elegiac artwork on which their film was based. Fans of Simon Stålenhag's illustrated novel gnashed their teeth; everyone else sat around for 2 hours waiting for something to justify the film's sumptuous visuals. *The Electric State* was so outclassed by its world-building and set design, you wonder the makers didn't build a theme park instead – it would have been a more artistically valid use of a stunning $320 million budget.

TCD/PROD.DB/ALAMY

In *The Occupant*, Abby (Ella Balinska) struggles across Georgian wilds

Bong Joon Ho's *Mickey 17* promised something different: a scenario in which blue-collar spacefarer Mickey Barnes (Robert Pattinson) is reduced to robotic servitude by being reprintable. Now here was something into which the director of *Parasite*, *Okja* and *Snow Piercer* could sink his satirical fangs. Alas, the film never trusted its audience, and choked on its own exposition.

"Taking chances while you attract a huge audience may be a trick Stanley Kubrick et al. took to the grave"

Sci-fi filmmakers have always been capable of dreaming up compelling extraterrestrials: think *Solaris*, *Arrival*, *Annihilation*, *Under the Skin*... So 2025's predeliction for monsters and satanic possession is less a sign of exhaustion than of the horror genre nipping in to play in its cousin's vegetable patch.

Director Scott Derrickson's hellish hollow men take an age to emerge from *The Gorge*, which weakened this intriguing part cold-war romance, part spy thriller, part Lovecraftian horror flick. When Miles Teller and Anya Taylor-Joy play elite snipers from different world powers, guarding a vast gorge in an undisclosed country, we are primed for more than 40 minutes of prologue.

Hugo Keijzer's *The Occupant* was rather more successful, as Abby (Ella Balinska) struggles across remote Georgian wilds, aided by a disembodied voice that, whether human helper or alien possessor, is externalising our hero's own guilt and grief.

We are on more solid genre territory with *Ash*, directed by Los Angeles musician Flying Lotus – one of those rare experiments that really is a feature-length music video, and all the more dazzling and brain-bending for it. Riya (Eiza González) wakes, amnesiac, on a space station full of bodies. Brion (Aaron Paul) arrives to help her, but is he what he seems? Is she? And why does the on-board AI warn of an unusual life form on the station? Again, familiar territory, but a welcome excursion.

It is no surprise that of the two standouts this year, neither had a particularly huge budget. Taking chances while you attract a huge audience may be a trick Stanley Kubrick et al. took to the grave.

Serpil Altin's *Once Upon a Time in the Future: 2121* is about a family deciding whether to bump off the elders to meet the "scarcity laws" of their hilariously zealous administration. Meanwhile, Joshua Oppenheimer's *The End* is a musical about a family deciding whether to execute an unexpected visitor – a choice they may have faced many times before.

These two, with *The Occupant*, give the lie to the idea that sci-fi plots must be original. Sci-fi is fiction; fiction is about people, and even in familiar plights, people are infinitely various. ▮

Editor's pick

A quantum view of the past, present and future

29 November, p 28

From Sue Tudor, Leeds, UK

With reference to the interesting article by Ciarán Gilligan-Lee on quantum cause and effect, I would point out something that I have often noted, but that is always overlooked.

History can be understood in quantum terms. The future is nothing but a series of probabilities, the present is where we "measure" them by experiencing them, the past is things that have already been measured. No observer is necessary to make these "measurements" – they would happen even if no life had ever existed. Each present of each individual entity exists independently and relative to all the others (in its own causal bubble), but all are consistent and fit into one coherent whole. And what drives the course of history except cause and effect?

Reality as we experience it, and the reality of the quantum world, are often typified as different. In fact, we have a parallel classical world and quantum reality always around us and observable at every moment of our lives.

The yin and yang of human evolution

15 November, p 19

From Matt Black, Moreton-in-Marsh, Gloucestershire, UK

Jonathan R. Goodman argues that the selfish gene view of evolution is correct and bemoans the "old and tired" debate on whether niceness and group selection trump that. It is this binary thinking that is old and tired. Evidence for each view exists and must be synthesised into a 360-degree view. Competition and cooperation are the yin and yang of evolution. Their interaction is the endless dance of behaviour and adaptation we call life.

Hearing aids that know which way you're facing

Letters, 22 November

From Adrian Kirkup, Salisbury, Wiltshire, UK

Richard Black asks if a hearing aid can be designed with software to selectively amplify sounds coming from the direction you are facing. I can tell him that my hearing aid does exactly that.

Instead of picking up all the sounds entering the ear and amplifying select frequencies, my hearing aid software can be set for "Conversation in Loud Noise". In theory, I can sit facing my wife in a crowded restaurant and forward-facing microphones amplify what she is saying, so I can hear her. In practice, they don't work quite like that. Yes, I can hear what she says, but I can better hear the ladies who are lunching a couple of tables behind her.

A counterpoint on biomass carbon capture

Letters, 22 November

From Eric Kvaalen, Les Essarts-le-Roi, France

David Flint says biomass carbon capture would require too much land area. He favours using chemical plants to capture carbon dioxide from the air. I would like to point out that, every year, about 440 gigatonnes of carbon dioxide enter the atmosphere from rotting vegetation, whereas we have about 1100 gigatonnes more carbon dioxide in the atmosphere than in pre-industrial times. In other words, if we could store all the biomass that rots, we could solve global warming in a couple of years. The problem isn't land area, it is how to collect and store vast quantities of biomass, and how to incentivise this.

A response to our review of Mars documentary

11 October, p 28

From John Brandenburg, Jacksonville, Oregon, US

As a contributor to the documentary *Blue Planet Red*, I would like to address the criticism in Simon Ings's review that xenon-129's presence in the Martian atmosphere implies ancient nuclear conflict only if you ignore the well-understood process by which a now-extinct isotope, iodine-129, would have decayed to xenon-129 in Mars's rapidly cooling lithosphere.

When Mars and Earth formed 4.5 billion years ago, they contained both iodine-129, source of xenon-129, and plutonium-244, source of xenon-132. The half-lives of both isotopes are comparable in geologic timescales and their decay products should have both outgassed by now.

On Earth, these isotopes are approximately equal in abundance in the atmosphere, but on Mars, there is 2.5 times more xenon-129 than xenon-132. The mystery is why the iodine-129 decay product shows up, but there is less of the plutonium-244 decay product.

Supernova and thermonuclear weapons both produce iodine-129 preferentially over plutonium-244. Mars didn't experience a supernova, hence I propose that the xenon-129 excess, along with other evidence, is explained by a thermonuclear holocaust.

Mystery still surrounds the dawn chorus

1 November, p 7

From Jonathan Wallace, Newcastle-upon-Tyne, UK

You report that a study by Satoshi Kojima and his colleagues may have solved the mystery of why birds sing at dawn, suggesting singing is suppressed by darkness, leading to a build-up of motivation that is released when the dawn breaks. This may explain the mechanism that mediates the diurnal pattern of singing, but it hardly explains why dawn singing has evolved. Other behaviours are also suppressed by darkness, so why, for example, do songbirds not respond to the daybreak with a burst of intensive feeding or some other behaviour?

Admiration for ancient cave paintings

22 November, p 34

From Alex Bowman, Glasgow, UK

Regarding the feature Songs from the caves, the Lascaux cave paintings in France include a star map of the Taurus region of the sky with a bull painted around the Hyades, just as the constellation is depicted today. Dated at 17,000 years old, surely this is the oldest provable human concept? After viewing this cave art, Pablo Picasso proclaimed: "We have learned nothing in 12,000 years."

Why it's futile to chase after perfection

15 November, p 28

From Terry Klumpp, Melbourne, Australia

On the discussion of knowing when to give up on your goals, I contend that longing for perfection of oneself is an exercise in futility and frustration. Why? Because none of us is perfect and, despite our best efforts, alas, none of us will ever be perfect. Let's all relax a little and not set ourselves unachievable goals. ▮

For the record

▮ **The Torino scale assigns asteroids a score of 0 to 10 based on their size, energy and probability of hitting Earth (15 November, p 38).**

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Unexpected origins

We have long puzzled over how life began. Now, evidence suggests a sinister protein may be the missing ingredient, says virologist **Michel Brahic**

IN 1944, Erwin Schrödinger published a book called *What Is Life?*. The physicist, famous for his alive-and-dead cat, clearly relished a brainteaser. Today, there is still no good definition. Life is generally agreed to require a minimum of two things: metabolism and reproduction. But the question of how chemistry morphed into biology billions of years ago is very much open to debate.

Now, a surprising contender has emerged as the catalyst for sparking the first life – and it is one we typically associate with deadly diseases.

Advances in molecular genetics have revealed that all living things on Earth are descended from a single organism dubbed the last universal common ancestor, or LUCA, which emerged around 4 billion years ago. We also know that our planet is approximately 4.5 billion years old. During those first half a billion years, simple, then more complicated, organic molecules were spontaneously synthesised and assembled in larger complexes, eventually evolving into the primitive, single-celled LUCA. How did that happen?

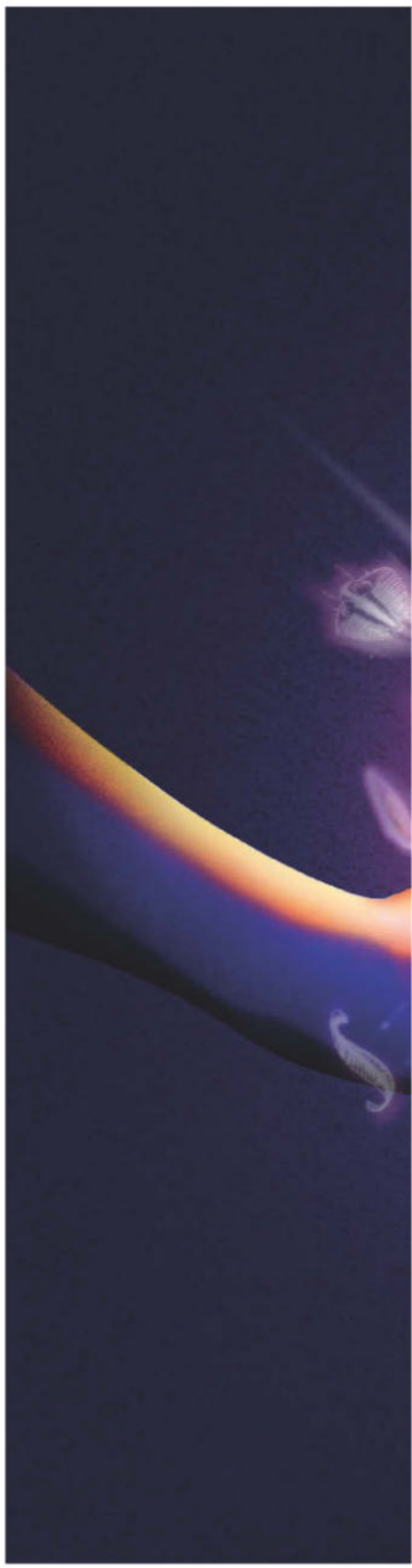
Biologists have long debated which key molecule of life came first. RNA – a cousin of DNA – has been a front-runner because some RNA may be able to copy itself. However, these molecules seem too unstable to develop into life. Another possibility is proteins. Here, the problem is that they can't reproduce. Now, some researchers are suggesting a solution to these roadblocks – and it comes from an unexpected quarter.

Prions are weird proteins, originally fingered as agents of infectious neurodegenerative diseases such as kuru and scrapie. That's how, as a virologist, I became interested in them. But it has become apparent that prions aren't, in fact, a malevolent rarity, but are found in many organisms, playing a host of crucial roles, from the immune system to memory formation. Could they also be the missing piece in the puzzle of life's origins?

Life requires metabolism – the ability to import useful molecules from the environment and jettison waste products. This allows organisms to produce energy to grow, persist and respond to their environment. But enduring isn't enough: life must also reproduce. As François Jacob poetically puts it in his book *The Logic of Life*: "Everything in a living being is centred on reproduction. A bacterium, an amoeba, a fern – what destiny can they dream of other than forming two bacteria, two amoebae or several more ferns?"

In the beginning, reproduction simply meant molecules that could copy themselves or that could be copied by interacting with other molecules. This gave them a chance to persist despite the inevitable degradation that happens over time. There would be no life if metabolising, replicating molecules hadn't appeared. How this happened is a central question for scientists working on abiogenesis – the emergence of life from inanimate chemicals.

One of the first people to explore this question was Stanley Miller. As a PhD student in the 1950s, he joined the laboratory of chemist and Nobel laureate Harold Urey at the University of Chicago. Miller then convinced a reluctant Urey to let him test his hypothesis that life started in ponds rich in salts, when the atmosphere contained hydrogen, ammonia and methane, with electricity from lightning



SARA GIRONI CARNEVALE

providing the required energy. To do this, Miller built an apparatus that recreated these conditions. After several days of continuous electrical discharges, he found that several amino acids, identical to those that constitute the building blocks of proteins today, had formed. This result was published in *Science* and became a classic in biology known as the Miller-Urey experiment, despite Urey having declined authorship of the paper to give Miller full credit.

Since then, a range of environments have been suggested as the place where life began. The shallow pond hypothesis is still favoured by some. They argue that the regular alternation between ultraviolet-rich light and darkness and between high and low temperatures caused by Earth's rotation on its axis created the cycles of synthesis followed by quenching of chemical reactions needed to stabilise the production of complex organic molecules.

When life emerged

However, most experts now believe that life got started at hydrothermal vents in the oceans or in hot springs where the temperature, pressure and chemical composition would promote the formation of these molecules. In the oceanic scenario, it is assumed that the rapid drop in temperature between the vent and the surrounding cold water provided the necessary quenching. Although Miller's experiment suggested life began with proteins, now the leading idea is that RNA came first.

This RNA world hypothesis goes back to the 1960s, when it was pioneered by several influential scientists, including Francis Crick, co-discoverer of the structure of DNA. One reason why it has been so enduring is that it addresses the issues of both metabolism and reproduction. RNA is a linear molecule comprised of building blocks called nucleotides made of two types of bases – purines and pyrimidines – and a sugar called ribose.

These organic components formed spontaneously and were subsequently linked together to make RNA, according to the RNA world hypothesis. Linear RNA molecules can fold into three-dimensional shapes that give some of them – called ribozymes –the abilities of enzymes. That is crucial because enzymes catalyse essential biochemical reactions that can only proceed with them: there would be no metabolism without enzymes. In present-day organisms, some enzymes are still ribozymes, although most are now proteins.

Another argument in favour of the RNA world is that RNA, like DNA, can encode genetic information – the basis ›

ZACK FRANK/SHUTTERSTOCK

Hot springs are one candidate for where life began

"The formation of LUCA from a soup of chemicals was an extremely unlikely event"

for Darwinian evolution. The order of the nucleotides in a strand of RNA forms a code that is copied when the molecule is duplicated. Like DNA replication, this requires enzymes called polymerases. Today, these are all proteins, but, since there would have been no proteins in an RNA world, the hypothesis requires that, back then, some ribozymes would have functioned as RNA polymerases.

Several scientists have attempted to recreate such ribozymes. For instance, in 2023, Annalena Salditt at Ludwig Maximilian University of Munich in Germany and her colleagues created ribozymes that could copy short RNA molecules, including the ribozyme itself, making more ribozymes. Others have even devised elegant experiments in which primitive ribozymes could mutate and evolve, acquiring new enzymatic activities.

The RNA world hypothesis has some flaws, however. A major one is that RNA molecules are very unstable in water, which means they would have quickly degraded in the sort of environment where life originated. To survive, they would have needed to be protected by proteins, but, by definition, there would have been no proteins in an RNA world. To get around this, several researchers have suggested that protection may have been provided by the tight folding of RNA molecules, along with them binding to physical supports such as clays or similar natural substances. Others, however, believe that the problem of RNA instability, as well as the difficulty of spontaneous synthesis of nucleotides compared with the easy synthesis of amino acids, undermines the RNA world hypothesis, and that proteins formed first instead.

Miller's experiment in the 1950s showed that amino acids form spontaneously under conditions that mimic Earth's primitive prebiotic soup. Since then, experiments have repeatedly confirmed the spontaneous formation of amino acids, including under the conditions found in hydrothermal vents at the bottom of the ocean and in hot springs. Amino acids are also commonly found on meteorites – they are components of the universe. Furthermore, in laboratory experiments that reproduce prebiotic conditions, amino acids link together to form chains like those in present-day proteins.

The RNA problem

The same cannot be said of RNA. Building an RNA world from scratch requires the spontaneous formation of purine and pyrimidine bases and ribose, their assembly into nucleotides and finally the linking of nucleotides to each other. However, such a chain of reactions has never been achieved in the laboratory under the conditions that prevailed during Earth's first half a billion years. All this makes the creation of a protein world far simpler to explain than the creation of an RNA one.

There's another advantage to the protein-first idea. Almost all the enzymes we know are proteins, meaning that metabolism would have been possible from the start. However, there is one major problem: today, RNA is required to carry the information to make proteins, and ribozymes are needed to link amino acids together, so it is unclear how a protein-only life form could have reproduced. This stumbling block explains why the RNA world hypothesis has dominated. Now, however, there is a possible solution – and this is where prions come in.

Prion was the name given by my colleague Stanley Prusiner to the agent of neurodegenerative diseases including scrapie in sheep and goats, bovine spongiform encephalopathy – or "mad cow disease" – in cattle and Creutzfeldt-Jakob disease in humans. They are infectious and can be transmitted by inoculation with contaminated material, just as viral diseases can. However, in the 1980s, Prusiner discovered that the agent of these diseases, the prion, is made of a single protein. There is no DNA or RNA, as there is in viruses.

The idea that a protein could be infectious was a bombshell. More recently, "prion-like" proteins – which are different from Prusiner's original prions and don't spread between individuals – have been found in people with common neurodegenerative conditions, including Parkinson's and Alzheimer's disease.

But the story doesn't end there. In my book, *The Power of Prions*, I describe how scientists have discovered that prion-like proteins are, in fact, common in organisms from bacteria all the way to mammals, suggesting they were retained during evolution because they had important functions. Indeed, some of these functions have been identified. Prion-like proteins are used by yeasts to adapt to changes in their food environment, for example. In animals, including mammals, neurons employ a prion-like protein to establish long-term memory. Others are used by immune cells in their fight against viruses. In other words, we need to rethink these proteins. The prions and the prion-like proteins responsible for disease appear to be exceptions in a family of useful proteins that has been associated with life for a very long time.

The thing that sets these proteins apart from other proteins is the way they fold. It is also what makes them central to the protein world hypothesis of the origin of life.

Proteins are chains formed from combinations of 20 amino acids, each with a different chemical structure, linked to its neighbour by a chemical bond called a peptide bond. The order of amino acids in the chain and its overall length vary widely, resulting in the enormous range of proteins found in nature. To play a biological role, including being an enzyme, a protein chain must fold into a very precise shape.

Prions are a type of intrinsically disordered protein, which don't fold spontaneously into stable shapes. They constantly fold and unfold into many thousands of unstable shapes,

lasting just milliseconds each. To fold properly, they need to interact with a partner that is usually a different protein. For prion proteins, though, the partner is another copy of the same prion protein that happens to be in the same unstable shape. The two bind together and form a stable pair that persists. It also recruits more copies of the unstable protein in this same shape and stabilises them. This process, called self-templating, creates a stack of identically folded prions or prion-like proteins that looks a bit like a pile of soup dishes. Eventually, it will form into long fibrils, which can be seen with an electron microscope. When a fibril fragments, it creates "seeds" that will initiate the formation of more fibrils. The protein is making copies of itself – it is reproducing.

Intriguingly, experiments reveal that these fibrils are extremely resistant to harsh environments, including those found in hydrothermal vents and hot springs. They have also been created in the lab by researchers attempting to make protein chains from spontaneously generated amino acids. In 2010, for example, Jacqui Carnall at the University of Cambridge and her colleagues created proteins that took the form of fibrils and also behaved as prion-like proteins, producing seeds and replicating. Later, several groups showed that spontaneously formed protein fibrils can have a large range of enzymatic activities.

These results prompted some researchers to propose that a protein world may have appeared very early on Earth, and before the RNA world. The sequences of amino acids and the sizes of these proteins must have been extremely diverse since they resulted from the random assembly of the amino acids that formed spontaneously in this environment. By chance, the sequence of some allowed them to form highly resistant fibrils with prion-like properties. Being prion-like, they would also have been able to replicate, enriching the milieu with more copies of themselves. Some of them behaved as enzymes with various activities, possibly including acting as the catalysts needed to build RNA. Over many millions of years, a collection of proteins with diverse enzymatic activities may have built up, setting the stage for the formation of LUCA.

Fight for survival

But that still leaves one big mystery. By the time LUCA appeared, it was equipped with an efficient mechanism to make proteins and reproduce. It had RNA and a way to translate the genetic information encoded in RNA into proteins. This complex operation is performed by a micro-machine called a ribosome, made of both proteins and RNA. All descendants of LUCA, from bacteria to humans, use ribosomes. In all of them, the enzyme that joins amino acids to make proteins is a ribozyme, made of RNA. What's more, this ribozyme is nearly identical in all present-day organisms, suggesting that it has been conserved because of some unique property. And it is special: protein enzymes tend to be very specific for their substrates, but this ribozyme can work with all 20 different amino acids, regardless of their structure and position in the chain.

The ribosome results from a remarkable collaboration between protein and RNA. We don't know when this collaboration began. However, an ingenious solution has been suggested, one that is finally taking us beyond the old debate about whether life began as protein or RNA.

The new idea posits that there was collaboration from the start. A number of researchers have suggested that several RNA worlds and prion-like protein worlds emerged spontaneously on the young Earth. Only a few of these survived the harsh environment for any length of time. Nevertheless, on some occasions, a protein world and an RNA world overlapped, giving RNA molecules a chance to be stabilised through interaction with proteins.

Among various RNA-protein assemblies, one formed a primitive ribosome, kick-starting an efficient mechanism of protein synthesis. These merged RNA-protein worlds also produced structures enclosed in membranes by combining with other spontaneously formed organic molecules, including lipids. Meanwhile, DNA appeared, providing a repository of protein sequences in the form of genes and helping these proto-cells to multiply. One was especially successful at dividing and evolving and became LUCA.

The formation of LUCA from a soup of chemicals was an extremely unlikely event, with a probability estimated at less than 1 in a billion. Other forms of life may have emerged, but they disappeared due to a lack of stability. LUCA was probably the lucky winner of a competition for survival run under strong evolutionary selection pressure. However, it is possible that alternative life forms may still be present – perhaps as microorganisms hidden in rocks – and that abiogenesis on other planets produced types of life different from ours.

In any event, these new developments in our understanding of the emergence of life place prion-like proteins – originally discovered as agents of disease – at the centre of a marvellous chain of events that first produced LUCA and then, after more than 4 billion years of evolution, led to us. ▮

"Prions aren't a malevolent rarity, but play crucial roles in many organisms"

GAROPHANIE/SCIENCE PHOTO LIBRARY

Prions are responsible for Creutzfeldt-Jakob disease in humans

Michel Brahic researches prion proteins responsible for degenerative brain diseases. He is Professeur Honoraire at Institut Pasteur in Paris

Beyond the horizon

Unravelling what's inside a black hole could reshape the foundations of how we think about space and time, finds **Adam Mann**

IMAGINE you're standing in front of a closed door. Behind it is a teenager's bedroom, and your task is to rate how messy it is on a scale of 1 to 10. But here's the twist: you can't open the door – and you don't even know what kind of stuff might be inside.

If that sounds a tall order, try being a physicist. For the better part of 50 years, they have been wrestling with the knotty problem of black hole entropy, a question about how messy or disordered these behemoths are on the inside. Everyone knows you can't see inside a black hole, but it's worse than that. No one is even quite sure what the concept of disorder means when you are talking about an epic, inaccessible hole in the fabric of space-time.

For decades, theorists have tried to answer this using the tools of quantum mechanics, only for their calculations to explode into meaningless infinities. But now, a breakthrough with an incredibly complex branch of mathematics has changed the game and finally allowed us to calculate the messiness of a black hole. The result was deeply unexpected, but it might just be telling us something new and profound about the way space-time works.

"We ultimately hope that this lesson about black holes isn't just about black holes," says theoretical physicist Gautam Satishchandran at Princeton University.

The first ideas about entropy were born in the steam age. Physicists like Ludwig Boltzmann grappled with why engines, no matter how cleverly they were designed, seemed to always lose energy in the form of waste heat. In the 1870s, he came up with an understanding of entropy that focuses on a hidden underworld.

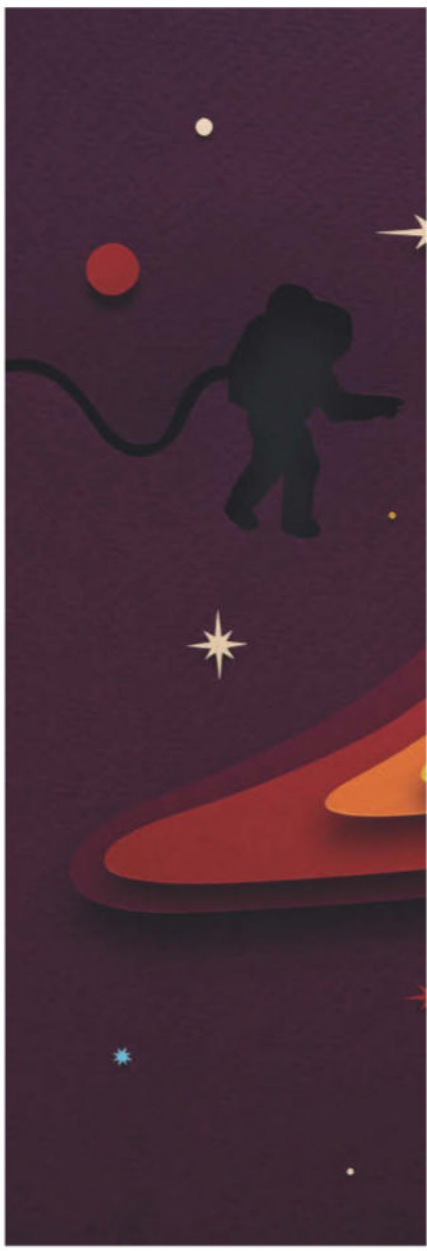
"[Boltzmann's] notion of entropy counts all the possible configurations of particles in a system that lead to the big macroscopic measurements we can make about it," says theoretical physicist Netta Engelhardt at the Massachusetts Institute of Technology.

Picture a room full of gas molecules, she explains, ricocheting off one another in chaotic motion. There are numerous ways to arrange these molecules, most of which involve them being spread out fairly evenly. Only a few would gather them all into one corner. Boltzmann realised that entropy was a measure of how many microscopic configurations, or "microstates", produced the same large-scale appearance. Swap two molecules and nothing changes – temperature, pressure, volume all stay the same. But behind that sameness lie vast numbers of potential arrangements.

This was a watershed moment. Boltzmann linked entropy to the invisible ballet of tiny atoms – a bold move, considering that scientists at the time still believed such particles to be a convenient fiction. Yet Boltzmann's equations predicted the behaviour of gases with such uncanny accuracy that they helped cement the atomic view of matter.

But then in the early 20th century, along came quantum mechanics, and with it a whole new perspective on entropy. In the 1930s, polymath John von Neumann extended entropy into the quantum world. There, particles don't have fixed properties like position or momentum. Instead, one can give only probabilities of finding certain outcomes when a particle is measured. Von Neumann showed that entropy could quantify the uncertainty inherent in quantum mechanics.

He also managed to capture the way parts of a quantum system can become entangled.



"For decades, physicists have been divided on what, if anything, exists inside a black hole"

OWEN GILDERSLEEVE

In an entangled system, two regions – or even two particles – can be so deeply connected that learning something about one instantly tells you something about the other, no matter how far apart they are. Von Neumann's entropy also considers how our knowledge of one part of a system may depend entirely on what we can observe in another.

But there's a crucial divide here between the two visions of entropy. Boltzmann's version came as a built-in feature of the world, a tally of the possible microscopic rearrangements you can make to the building blocks of a system. Von Neumann's, by contrast, captures our imperfect knowledge of the quantum world. Boltzmann's entropy is a statement about what is; von Neumann's is a statement about what we know.

There aren't many people who can say they got one over on Stephen Hawking. Yet that is exactly what Jacob Bekenstein, then a graduate student at Princeton University, did in the early 1970s. He argued that black holes had to have an entropy – or else you could violate the second law of thermodynamics, which says the universe's total entropy must always increase. Throw something into a black hole, and its entropy would vanish. That didn't add up.

Hawking was unimpressed. Entropy, as every self-respecting physicist knew, was a measure of disorder, a kind of physical bookkeeping for what's going on inside a system. And black holes, by definition, had no insides.

But in trying to prove Bekenstein wrong, Hawking instead discovered Hawking radiation, a quantum glow around black holes generated by particle-antiparticle pairs near the event horizon. This radiation implied ›

black holes have a temperature – and where there's temperature, there must be entropy.

Hawking later joked about putting the black hole entropy equation on his tombstone. "Hawking and Bekenstein essentially set off the field of black hole thermodynamics," says Jonah Kudler-Flam, a theoretical physicist at the Institute for Advanced Study (IAS) in Princeton.

This discovery just raised more questions. Boltzmann tied entropy to something physical: the hidden microstates of a system. So if black holes have entropy, did that also imply they had a hidden interior? For decades, physicists have been divided on what, if anything, exists inside a black hole – but the hope was that they could recreate Boltzmann's magic and use entropy to figure out the underlying microscopic structure.

NASA/JPL-CALTECH

We can see only some of the universe – entropy could help us investigate beyond this limit

Atoms of space-time

Just what would this structure be? An arrangement of particles that had fallen beyond the event horizon? Or something stranger, like entangled bits of quantum information? Some physicists even suspect these hidden ingredients might not be particles at all, but more abstract building blocks – the elemental units from which space-time itself emerges. "We're trying to understand what are the atoms of space-time," says Jonathan Sorce, a theoretical physicist at MIT.

Crack that mystery and physicists might not just understand black holes – they might glimpse the long-sought unification of general relativity and quantum theory. These two great frameworks of modern physics collide most violently inside black holes. By understanding what these gravitational monsters are made of, we might finally bring both theories under the same roof.

For decades, researchers struggled to make headway. That was partly for obvious reasons. "We can observe the exterior of the black hole," says Sorce. "But we are totally ignorant to what's inside it, because it is literally a black hole."

But it was partly also because of mathematical limitations. In the wake of the Hawking-Bekenstein breakthroughs, theorists had turned to the quantum view. Maybe von Neumann's entropy, which uses a kind of mathematical tool set called operator algebra, could expose something about the invisible structure of space-time inside a black hole. Yet every time they tried, the quantum approach kept ending in failure, yielding the hardest kind of results to reconcile with tangible reality: a slew of infinities.

Boltzmann wanted to know why steam engines lost energy in the form of heat

BETTMANN/GETTY IMAGES

The reason, says Satishchandran, lies in the nature of von Neumann entropy itself. It is measuring what can be known – what a quantum observer can, in principle, detect.

Imagine drawing a boundary around a chunk of space – the region between two stars, say. What can you know about it? In quantum theory, there are no built-in limits on what you can measure. Zoom in as far as you like; space can always be sliced finer, revealing more detail.

"If you ask me what I can measure about some volume of space, the answer is infinity," says Satishchandran. "I can know an infinite number of things about it to an arbitrary precision."

The problem runs deep. The mathematics of quantum theory, operator algebras included, wasn't built to handle gravity. It treats space-time as a fixed stage. But general relativity says space-time bends and flexes in response to matter and energy.

That discrepancy hardly matters in most quantum systems, where gravity is so weak it can be ignored. Yet near a black hole, where quantum fields roil in violently curved space-time, that blind spot breaks everything, and it shatters hopes of uniting the strange world of quantum theory with general relativity more generally.

But in 2023, a team of theorists, including string theory heavyweight Ed Witten at the IAS, decided to flip the script. What if they stopped treating space-time as static and instead allowed it to take part in the quantum churn? Using the mathematical machinery of operator algebras, they wove gravity into the calculations from the ground up.

The maths is fiendishly complex, but the idea is simple: quantum fields tug on space-time, and space-time tugs back. This feedback loop proved to be the missing ingredient – stabilising the calculations and stopping them from spiralling into infinities. "Normally, when you give me two badly behaved things and add them together, I would expect something worse," says theorist Daine Danielson at Harvard University. "The fact that they're badly behaved in equal ways is a glimmer of some deeper structure that's better behaved."

This theoretical breakthrough laid crucial groundwork for Satishchandran and his colleagues to pick up the thread. Earlier this year, they used Witten's tweaked mathematics to calculate the von Neumann entropy of a black hole. By taming the infinities, they could measure how the black hole's external surface is entangled with bits inside – a bridge between inside and out.

What they found was striking. The entropy of a black hole, the one first calculated by Hawking and Bekenstein using thermodynamic arguments, turned out to be exactly equal to the von Neumann entropy. It's a powerful convergence. On one side, von Neumann entropy measures what we don't know in a quantum system. On the other, the Bekenstein-Hawking entropy measures a physical property of space-time. And yet here they are, the same.

If that sounds wild to you, you're not alone. "I think it's very provocative," says Danielson. It echoes the original shock of quantum mechanics: that reality isn't just what is, but what can be measured. And now, black holes seem to follow the same rule. The entropy we observe outside – once considered a thermodynamic oddity – turns out to be a faithful stand-in for everything going on inside.

It's a big revelation, akin to finding out that standing outside the door of that teenager's chaotic room is enough to deduce exactly what's inside. It goes beyond the interior that Bekenstein and Hawking hinted at decades ago. We no longer just suspect there is something behind the horizon, but that we may also never need to peer inside a black hole to decode its full story.

The precise ingredients of a black hole, whether quantum fields or tiny vibrating strings, remain unknown. But physicists believe that careful measurements near the event horizon could eventually be enough to reconstruct its quantum structure.

The line between what's real and what's observable is growing thinner. "Right now, we see many pieces of a bigger jigsaw puzzle," says Hong Liu, a physicist at MIT. "Whether we have all the pieces, we don't know."

Black holes aren't the only cosmic boundaries drawing attention. If entropy reveals something essential about space-time at a black hole's edge, perhaps it can do the same at the universe's outer limit.

That edge, called the cosmological horizon, marks the furthest we can observe. Because the universe's expansion has outpaced light since the big bang, there are regions from which no signal – no light, no information – will ever reach us. Eerily, these horizons behave much like a black hole's event horizon: what lies beyond is unknowable.

Hawking extended his entropy calculations to this boundary too. The result, the Hawking-Gibbs equation, mirrors his black hole formula, encoding the entropy of an expanding universe in the curvature of space-time.

"The implication is startling: gravity may not be a fixed, universal force at all"

Von Neumann entropy is used to operate quantum computers

KENT NISHIMURA/BLOOMBERG VIA GETTY IMAGES

Satishchandran and his colleagues applied the same operator algebra tools to these cosmic horizons, asking whether entropy could also describe how space-time behaves here – and offer more clues to quantum gravity.

Imagine all the information that can possibly reach you from the universe's distant corners, says Satishchandran. That stream of light is shaped by the geometry of the space it travels through, the structure of space-time, but it is also defining the limits of what we can possibly measure and know. Once again, we see entropy split along familiar lines: one shaped by what is, the other by what we can observe. In working through this tension, physicists hope to tease out what space-time is truly made of.

So far, the results have been uncanny. Satishchandran and his collaborators have once again found that the Hawking-Gibbs entropy – this expression of space-time's geometry – is equal to the von Neumann entropy, the measure of quantum uncertainty.

"It's extremely suggestive," he says. And it leads to a profound implication: that gravity may possess some of quantum mechanics' stranger behaviours.

Other research with the same approach has come to similar conclusions. Early this year, a team at the Okinawa Institute of Science and Technology in Japan published a paper arguing that gravity itself is observer-dependent.

Because different observers access different parts of the universe, the researchers argue, this shapes what they can measure. On a quantum level, that changes the information they can extract – and with it, the entropy they assign to a region of space-time.

And because gravity is encoded in the geometry of space-time – and geometry, in turn, encodes entropy – the implication is startling: gravity may not be a fixed, universal force at all. It could emerge differently for different observers.

But the path to a full theory of quantum gravity, says Satishchandran, is still far from complete. What's emerging now is just the latest leg of a journey that began, improbably, in the 19th-century science of steam engines.

"Operator algebras might not be the final answer," he says. "But they've opened a door that wasn't there before. Now we're trying to see how far we can push it." ▮

Adam Mann is a journalist specialising in space and physics

GUIDO MIETH/GETTY IMAGES

Would you make yourself sick for science?

People are willingly becoming infected with diseases in order to discover how our immune system fights back. What motivates them, asks **David Adam**

AT FIRST glance, you would think it was a modest hotel. There are en-suite bedrooms, a socialising area with table tennis and pool tables and even on-call staff. Despite appearances though, this unassuming glass-fronted building on the outskirts of Antwerp, Belgium, isn't a place where people come to rest their heads ahead of a day's sightseeing. Instead, inside, healthy volunteers are swallowing virus-laced drinks, being sprayed with pathogens and waiting to deliberately fall ill.

Welcome to Vaccinopolis, a €20-million facility built by the University of Antwerp for a singular purpose: to infect people with diseases. The building, completed in 2022, specialises in running "human challenge trials", experiments in which small groups of volunteers are exposed to diseases under tightly controlled conditions with the aim of fast-tracking vaccine development and monitoring infections as they unfold in real time.

Deliberately infecting people with nasty diseases in the name of science isn't a new idea: human challenge trials have helped us understand and treat diseases such as typhoid for decades. But they have long existed on the margins because they were too rarely used for most researchers to be aware of them, as well as due to ethical concerns. Now, that's beginning to shift. The urgency of the covid-19 pandemic adjusted the calculus of many scientists and policy-makers, bringing fresh attention to the idea of challenging people with some of the world's most persistent pathogens and diseases, like norovirus and malaria.

The draw of these trials is speed. Their design allows scientists to test a candidate vaccine with a fraction of the participants of conventional trials and often in a matter of weeks. Now, with bespoke centres like Vaccinopolis facilitating such research, far more people are getting sick on purpose in the hope of speed-running new treatments.

There is a long history of scientists deliberately infecting people in the name of progress. Edward Jenner famously developed the first smallpox vaccine after purposefully infecting a young boy with cowpox and then repeatedly exposing him to smallpox to create immunity. But such history includes much darker episodes. During the second world war, German and Japanese researchers used prisoners of war as test subjects, infecting them with diseases like tuberculosis and plague. Many of them died.

Against this backdrop, as well as amid fears of causing long-term damage to participants, human challenge trials have seemed troubling. The covid-19 pandemic – with its grim death toll and rampant economic damage – shifted the conversation, however.

"There's been a step change in the recognition that these studies have value and can be ethically acceptable," says Christopher Chiu, an infectious disease researcher at Imperial College London. "I think any doubt about that has largely disappeared." In 2021, he led the world's first covid-19 challenge trial, in which he exposed 36 healthy volunteers between the ages of 18 and 30 to the SARS-CoV-2 coronavirus.

Eighteen developed an infection and were closely monitored for four weeks. The study yielded invaluable insights, showing that even low doses of the virus can cause infection, but that younger people were more likely to have milder symptoms. Chiu is now leading a new project that will test the next generation of covid-19 vaccines, with trials scheduled to begin by the end of the year. "We are trying to accelerate the development of vaccines which stop infection completely and therefore stop transmission," he says.

And it isn't just covid-19. These trials are increasingly being used to test cutting-edge vaccines against some of humanity's most enduring pathogens. Take norovirus, the notorious winter-vomiting stomach bug. It kills about 200,000 people a year and mutates fast enough to outpace the immune system, making it a tough target for vaccines. Earlier this year, scientists at San Francisco biotech firm Vaxart decided to try a new approach to working out a vaccine's efficacy. In a clinical trial, more than 100 volunteers were asked to drink norovirus-laced shakes. About half had been given a tablet of the company's experimental vaccine a month earlier.

By tracking who got ill, and how severely, scientists were able to assess how well the protective pill worked in just over a week. The results were promising. Vaccinated volunteers showed milder symptoms and shed less virus from both ends of their digestive tract, suggesting the vaccine could both protect individuals and reduce transmission.

Collecting this sort of data in such a short amount of time sounds especially impressive if you contrast it with the timelines of conventional vaccine trials. These require large numbers of participants in the hope that enough people will naturally contract the disease to generate statistically meaningful comparisons between vaccinated and unvaccinated groups.

That can be a problem when the infection rates are naturally low, as was the case in past Ebola outbreaks. Often, so few people caught the virus that vaccines couldn't be effectively tested – not because they didn't work, but because there weren't enough cases to prove that they did.

Infection control

By controlling who gets infected, challenge trials sidestep this issue, with far fewer participants needed to get early answers. While challenge trials won't replace large-scale clinical trials entirely – regulators will still want to see real-world results at scale – they help researchers prioritise which vaccine candidates are worth pushing forward. Both currently approved malaria vaccines were identified in these kinds of challenge studies, says Chiu, before progressing to broader trials.

But speed isn't the only advantage of challenge trials. Because participants are infected in carefully controlled settings, with researchers able to dose a participant with exact amounts of a pathogen, tracking a disease from the moment it takes hold becomes possible. That level of detail offers a window into how pathogens behave and how the body responds, paving the way for future ›

Vaccinopolis is the place to stay if you are willing to risk illnesses like flu or norovirus

RIGHT & BELOW: JONAS ROOSENS/BELGA NEWS AGENCY/ALAMY

treatments and offering the potential to shape public health policy.

That's the promise of Vaccinopolis, the residential quarantine facility in Antwerp built to host human challenge trials. The facility has 30 private bedrooms, each with a bathroom, fridge and microwave and is equipped to test pathogens up to biosafety level 3, the category that includes the coronavirus, as well as the nasties responsible for plague and tuberculosis. While participants in trials involving those sorts of diseases will remain confined to their air-filtered, negative-pressure rooms, during tests of less

> "For the next day or two, it was like Chekhov's gun was hanging on the wall and I was just waiting for it to fire"

dangerous diseases, such as influenza, they will be able to mix in social areas, provided they wear masks to avoid influencing each other's immune responses.

This more relaxed approach awaits volunteers in mid-2026, when Vaccinopolis will host a study on how influenza spreads, part of the effort to sharpen our tools and understanding before the next pandemic threat emerges. Pierre Van Damme at the University of Antwerp is the research centre's director. In the upcoming flu study, his team will focus on a localised response called mucosal immunity – the body's front line of defence in the nose, throat and lungs against airborne pathogens. Van Damme and others think that boosting this initial immune response could be the best way to develop vaccines that not only prevent illness, but also block further transmission.

Conventional vaccines train the immune system to stop people from falling ill, but that doesn't mean they prevent the spread of infection. A vaccinated person may still carry and transmit the disease to others, even while they don't show symptoms themselves, something the anti-vaccine movement used to falsely claim that covid-19 vaccines were ineffective.

Mucosal vaccines, usually delivered via nasal spray or oral tablets, take a different tack, aiming to trigger immune responses in the common entry points for bacteria and viruses. Stop a pathogen there, and you may prevent both illness and its onward spread.

"Then I think we are really moving to vaccinology 2.0," says Van Damme. "You open a completely new dimension because herd immunity will then be obtained much more easily." Human challenge trials are, for now, the only way to study mucosal immunity with the precision required to track the subtle immune responses involved, he says. "This is the first step to better understand mucosal immunity in a controlled situation."

Several mucosal covid-19 vaccines have already been approved in countries including China, India and Russia. But so far, there is little data on whether they block transmission. That's what Chiu hopes to find out in his new challenge trial. "We've asked for developers to come to us with their vaccine candidates, which we will test," he says. "We'll try and show they do a better job at preventing infection and transmission than the injected vaccines."

If the idea of coming down with a horrible infection while physically isolated from everyone you know and love doesn't have you gagging to join a challenge trial, you wouldn't be alone. Learning to select the right

Disease progression is easily tracked thanks to samples taken inside Vaccinopolis

THOMAS ANGUS/IMPERIAL COLLEGE LONDON

Christopher Chiu conducted the first human challenge trial for covid-19

volunteers is something Van Damme and his team have picked up from previous trials. Attitude is key. "What is important is that the people complain as little as possible," he says.

One such candidate is Jake Eberts, who joined a 2022 challenge trial run in a dormitory by the University of Maryland to test a vaccine against *Shigella*, a bacterium that causes dysentery. "The idea sounded a little bit nuts to me. It sounded medieval," says Eberts, now a consultant based in Washington DC. But Eberts says he was motivated to join anyway for the chance to move the needle on a disease that takes 600,000 lives every year, with the highest incidence among children under the age of 5.

"I was a guy born in Texas in a clean, safe hospital who never had to worry about the dozens and dozens of horrible, horrible diseases that regularly plague children across the world," says Eberts. The money he got as compensation for joining the study – $7350 – also helped make the decision easier. "I'm not Mother Teresa. I would not have done this for free," he says.

A month after receiving a shot of either a vaccine or a placebo – he still doesn't know which – Eberts was called into the isolation facility with about 15 other volunteers and given a glass of *Shigella* solution to drink. "Then for the next day or two, it was like Chekhov's gun was hanging on the wall and I was just waiting for it to fire," he says. Bang. "It hit me at midnight on a Friday," he says. "I was one of the sickest in the cohort. The doctor told me I was a real overachiever." Once the illness was confirmed the following day, Eberts was given antibiotics and rehydration, and by Monday, he was fine and working remotely. He was discharged two days later.

As brutal as his experience was, Eberts says he is very aware that it was nothing compared with what most of the 165 million people who contract *Shigella* infections each year worldwide go through. Eighteen months later, he volunteered again, this time for a Zika challenge trial. "Zika was much more chill than dysentery," he says. "I did try to do a third, for malaria, but that was cancelled."

The results from his *Shigella* vaccine challenge trial were published last year. The vaccine showed modest benefits: diarrhoea rates dropped from 82 to 68 per cent, and fever from 68 to 55 per cent. The biggest effect was against severe symptoms of dysentery, such as diarrhoea combined with other symptoms like fever, nausea or pain, with a reduction from 55 to 18 per cent. The vaccine is still being investigated and was recently tested in a field trial in Kenya, including in 200 infants under the age of 1.

Risky business

Challenge trials are designed to minimise the risk to volunteers like Eberts: short-term effects only and a guaranteed "rescue" treatment that can halt the disease if participants get too sick. But not all pathogens are considered suitable.

In 2017, ethicists blocked a proposed Zika trial on the basis of "concerns that it could cause lasting paralysis or be transmitted unknowingly to sexual partners". By the time of Eberts's Zika trial, the risk of men with the virus infecting their sexual partners was considered to be lower, although he and other participants were still told to abstain from sex or to use protection for several weeks afterwards.

The line between acceptable and unacceptable risk remains central to how future human challenge trials will be run. Unlike conventional trials, volunteers often receive no direct benefit to their health. They may not be at risk from an ongoing outbreak, or may not be sick and hoping for a cure.

Indeed, some ethicists remain uneasy. Charles Weijer at Western University in Canada argues that early covid-19 challenge trials ignored long-term uncertainties, including the risk of long covid. "There are important ethical constraints on challenge studies, and I think that in the context of covid-19, people were just not paying attention to those constraints," he says. "There was virus everywhere, so doing big field trials was actually really straightforward."

Chiu disagrees, saying that with so much transmission already happening in the UK, most volunteers would have become infected at some point anyway. Follow-up studies also showed long-term effects were rare for the young, healthy people who volunteered. In Chiu's covid-19 trial, the only lasting complication reported was a single case of loss of sense of smell, which was later recovered. Like Eberts, volunteers were paid for their time, to the tune of £4500. That might sound like a lot, but given they spent up to 16 days in quarantine, it works out at less than £12 per hour.

"I do think it's appropriate to compensate people for their time," says Weijer. "Generally speaking, that's benchmarked at something like minimum wage." Incentives to keep bringing in the volunteers needed to power these trials are crucial. A database of trials maintained by 1 Day Sooner, a US-based research advocacy group, shows more than 60 ongoing or planned challenge studies aimed at developing potential treatments for diseases like gonorrhoea and yellow fever, as well as tropical parasites like the whipworm and hookworm.

Still, Eberts maintains that altruism is his biggest motivator. "I kind of had won [the] cosmic lottery and it felt good to give back." ▮

David Adam is an author and journalist who covers science, technology and medicine, and the impact they have on society

Sponsored by DEEP

How aquanauts will change our view of the ocean

Vanguard, a new subsea human habitat, will immerse researchers for weeks, allowing them to observe the ocean's complexity and rhythms from within

DAWN Kernagis loves telling marine biologists about what's now possible. "Their eyes light up, and then they can't stop talking about all the things they'll be able to do," she says.

Kernagis is Director of Scientific Research for DEEP, a design and engineering organisation that has just designed and built a new subsea habitat called Vanguard. Unveiled in October in Miami, Florida, the habitat is the first step towards a new era in marine biology where scientists can live for weeks or months in the environment they are studying.

As well as revolutionising science, Vanguard is set to change the human relationship with the ocean, Kernagis says. "We're going to have people coming back from their subsea experience who will open our eyes to the underwater world, like astronauts did with space," Kernagis says.

Researching the marine environment usually brings a number of time constraints, not least of which is getting to and from the dive site by car on shore and then by boat. Then there is the amount of breathable gas you can take down and the pre- and post-dive tasks – such as pausing for decompression stops on the way back up. "You typically lose four or five hours in travelling and only get about an hour's worth of actual underwater work done per dive," says Roger Garcia, DEEP's Director of Habitat Operations.

Live at ocean pressure, though, and all that wasted time is gone. "Within 15 minutes, you can put your equipment on, go through your checks and go out and do your research for up to nine hours a day," says Garcia.

Vanguard, which has living and sleeping spaces, can facilitate stays of weeks or months at depth. Once they are at ocean pressure, divers' body tissues reach "saturation", where the concentration of breathing gases is in equilibrium. This changes the calculus of ocean science, opening up a new era in how humans can live and work undersea.

It's an opportunity that excites Jim Brittsan, the founder of Miami-based Sustainable Oceans and Reefs (SOAR), an organisation dedicated to advancing marine conservation. "Living under the sea fundamentally changes how research can be conducted," he says.

Vanguard can be fully equipped as a research lab, with state-of-the-art facilities for human biological science as well as ocean science. Samples from the environment or from the divers themselves can be analysed without the stresses of decompression.

Environmental immersion

"I love the idea of being able to process those samples at depth," Kernagis says. She points out that RNA expression levels in divers' blood have a distinct signature related to decompression, but this can mask other potential changes that occur during a dive. In analysing samples taken on the surface, we weren't actually seeing what was happening at depth, she says. Physiologists should get a better understanding with samples taken during long duration underwater stays.

Perhaps most exciting, though, is the coral restoration science that becomes possible over extended periods. "Maximising coral growth is time-consuming work," Kernagis says. "With Vanguard, you can amplify your time building out the coral nurseries, and you can do the monitoring and the maintenance – going out and on the coral garden – which has been a big gap when it comes to coral restoration. Plus we're able to do it deeper than with regular scuba."

Brittsan shares Kernagis's enthusiasm: it has been hard to do large-scale studies of coral communities at depth, he says. Vanguard could be a game-changer on this front. "Vanguard creates the opportunity to immerse yourself in that environment: to observe natural processes as they happen."

That means observing the routines and rhythms of the ocean from within, including the "diel vertical migration", the largest daily migration of biomass on Earth as creatures ascend from the depths to feed and descend again to avoid predators. Researchers will also see transient events like mass coral spawning and predator-prey interactions.

Vanguard is just the start of this new era: it is a pilot habitat that is preparing the ground for a much more permanent presence under the sea. DEEP is already building larger, more flexible habitats that will allow humans to become aquatic. "That's our vision," Kernagis says.

Vanguard can house up to four aquanauts for missions lasting weeks

Find out more at: www.DEEP.com

AQUANAUT, KNOW THYSELF

One of the biggest opportunities with Vanguard is the chance to study what happens to the human body during extended stays in pressurised conditions. These "hyperbaric" environments are likely to change body tissues in ways that are not fully understood, Kernagis says – even whether the changes are reversible.

For example, one emerging area is the study of epigenetic effects, where the pressures of the ocean environment alter the way genes are expressed, potentially affecting body function.

Remote habitat

Living in the ocean has similarities with living in space, and NASA has used previous undersea habitats to help prepare astronauts for the isolation and demands of living beyond Earth. Kernagis has worked as a saturation diver supporting NASA and is looking forward to the opportunities that Vanguard will make possible. "We really want to have a broader understanding of how humans respond to this kind of environment," she says. "The astronauts that I've worked with say that those undersea analogue missions have been very important for being able to test out the different technologies and the team dynamics."

Vanguard will enable the study of the psychological effects of long-term isolation in a remote habitat. While NASA has studied the psychology of the space environment, a subsea habitat has its own factors, Kernagis reckons. "You have the psychological pressure of being in a high-risk environment: you have to make decisions that can affect not just your safety, but your team's safety." And divers can't just bail out: head too fast to the surface and they'll suffer life-threatening decompression sickness, or "the bends". "It's not a Mars mission but it's still going to be really telling about human dynamics," says Kernagis.

Dear David

I think we're alone now

We can feel lonely even when we're surrounded by a festive crowd. **David Robson** digs into the psychological literature for a solution

David Robson is an award-winning science writer and author of *The Laws of Connection: 13 social strategies that will transform your life*

Resources

The psychologist Kristin Neff's website provides many strategies for practising self-compassion, many of which emphasise the "common humanity" that links us to others: self-compassion.org/self-compassion-practices/

Burnout coach Anna Katharina Schaffner's forthcoming book *The Story Solution: Change your toxic self-stories and thrive* (Profile, 8 January 2026) offers some eminently practical strategies for dealing with sadness, including the false belief that we are tragically different from other people.

Dear David, an evidence-based advice column, appears monthly. Drop David a line with your social dilemmas at davidrobson.me/contact

Next week

Stargazing at home

AS WE enter the holiday season, one Dear David reader is dreading loneliness this Christmas. It isn't that she lacks friends or family, she says, but that she sometimes finds the enforced jollity of work parties and family gatherings to be alienating. "I feel like I'm the only person not having fun," she says. "I don't mean to be a party pooper, but I find it hard to get into the festive spirit when I'm already struggling with my mental health. I end up feeling lonelier than if I'd stayed at home."

Feeling alienated in others' company – named "existential isolation" in the psychological literature – can happen to anyone at any time in life. Psychologists define it as the sense that no one sees the world through our perspective or understands how we are feeling, even when we are surrounded by other people. Those who score highly on measures of existential isolation are at a greater risk of conditions like depression and tend to be less responsive to treatments.

The irony is many people are probably feeling the same way, yet we assume that our pain makes us different so we don't share how we feel, contributing to our sense of isolation. That's why psychologists now encourage people to cultivate a sense of "common humanity" when they are feeling down. Put simply, this is the recognition that others may be in our position, so we don't need to feel a sense of failure for simply being unhappy.

Building a sense of common humanity can explain why "peer support" groups, which link up people facing similar problems, tend to be so effective in improving people's well-being. They release you from that sense of existential isolation, which provides its own kind of solace independent of the practical help that they may also offer.

FRANCK REPORTER/GETTY IMAGES

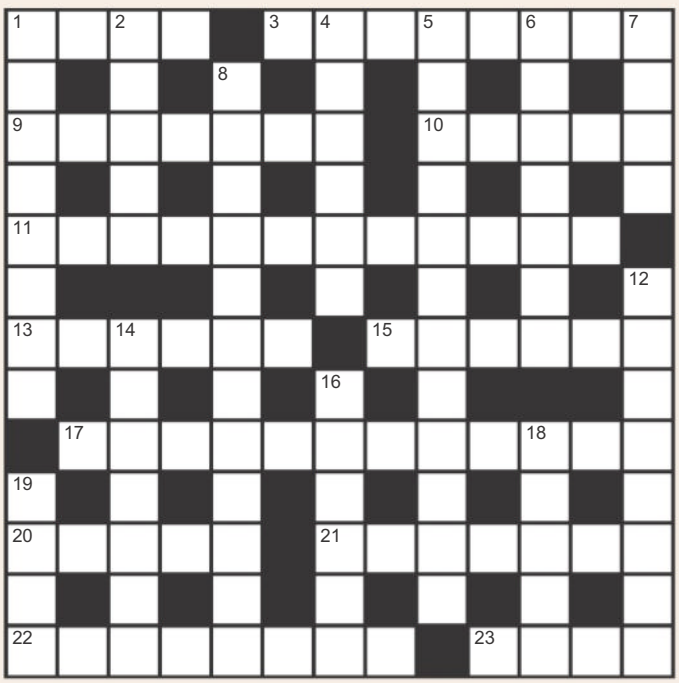
If you are feeling existentially isolated this holiday season, simply reminding yourself that you aren't alone in this experience may help. That's a core part of "self-compassion" training, and there are many online resources to help you to do this via writing exercises or guided meditation.

Even better, you might consider breaking the taboo by sharing how you feel, even if it doesn't feel very festive. Research suggests you may be surprised by people's reactions. Studies examining the "beautiful mess effect" show we are often needlessly pessimistic about others' responses to our problems. We assume we will be seen as weak, whereas people are more likely to see courage – and they may even share very similar feelings themselves.

As for those parties? Don't be obliged to accept every invite, and focus your energies on those that are most likely to create a sense of connection. A coffee with a trusted friend may do far more for your well-being than a festive disco. Christmas is a time of goodwill – and you can begin by directing that kindness at yourself. ▮

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

Cryptic crossword #176 *Set by Trurl*



Scribble zone

Answers and another cryptic crossword next week

ACROSS

1 Peaceable sort entered head-first (4)
3 Modern couple with unit somewhere on Tyneside, perhaps? (8)
9 South African student colours announced through trumpet-like organ (7)
10 Wildly exalt rubbery stuff (5)
11 Down trousers? Duke of Edinburgh may require them (8,4)
13 Lure companion back, almost (6)
15 Charlie wearing make-up right now (2,4)
17 Mutter rudely about tree-hugging Green who doesn't come to the office? (12)
20 Inflamed regarding quantity of liquid (5)
21 Newly arrived sodium smell (7)
22 Put a team in motion and take off (8)
23 Energy calculation reversed, making birds incapable of flight (4)

DOWN

1 Underworld flower is cause of lamentation (8)
2 Outlet seen in survival vent (5)
4 Curse a gas that's used as solvent (6)
5 I help bottoms, after retraining as a medical professional (12)
6 Onset of nausea follows careless eating, which may trigger immune response (7)
7 Post personal data in Day-Glo envelope with two kisses at the bottom (4)
8 Most of show's material used for constructing Archimedean principle (12)
12 It rusted, collapsed, leaving wreckage (8)
14 Area of high growth to peter out (7)
16 Buzzer, or hooter, before extra time (6)
18 Article on Molière radius generates a bit of heat! (5)
19 Parasite found in leaf cycle? (4)

Our crosswords are now solvable online
newscientist.com/crosswords

Quick quiz #331
set by Tom Leslie

1 Which country began a cloud-seeding programme on 15 November to alleviate extreme drought?

2 We recently reported that Canadian researchers had made a 3D-printing nozzle from which animal body part?

3 A recent discovery suggests the autoimmune condition lupus is caused by which common virus?

4 Astronomers have found an unexpected structure in the Kuiper belt. Beyond the Kuiper belt lies another debris field, also named for a Dutch astronomer. What is it called?

5 Google released what version of its Gemini large language model last month?

Answers on page 47

BrainTwister
set by Graham Smith
#102 Ladderet

This ladder shows how to go from one five-letter word to another by changing precisely two letters at a time. Each step should produce a valid word in the dictionary.

BAYES
GAMES
GAMMA
LEMMA

Which two words go between "brief" and "quark"?

Which two words go between "racks" and "brain"?

Which two words go between "sonic" and "lumen"?

Which two words go between "spill" and "atoms"?

Answers next week

Listen up

What part, if any, do my ears or auditory system play when I generate a tune in my head?

Professor Andrea Helpern and Professor Katie Overy
University of Edinburgh, UK
We invite you to imagine the tune of *Happy Birthday* right now! When you imagine this familiar melody, your ears aren't involved, but some parts of the brain associated with the auditory system do become active – not usually the primary auditory cortex (PAC), which processes sound signals, but the secondary auditory cortex, which is involved in analysing and organising sounds to make sense of them.

In addition to the auditory system, brain areas associated with working memory (dorsolateral prefrontal cortex) and sequencing (supplementary motor area) also become active. And if you start playing around with tunes in your head (try to imagine the first phrase of *Happy Birthday* backwards), then areas associated with attention and focus also become engaged (parietal lobe). So, generating

"Generating a tune in your head involves a lot of cognitive skills that take place in 'real time' and can even be developed"

a tune in your head actually involves a lot of cognitive skills.

These skills can take place in "real time" – most people can keep a steady tempo in their imagined melodies – and can even be developed. For example, composers and improvisers can create new music in their heads without any sound input. Interestingly, individuals who report more vivid imagined melodies show increased activity in the secondary auditory cortex and more connections between auditory and working memory areas. In contrast, individuals who experience auditory hallucinations actually show a reduction of activity in the PAC (compared with controls) when listening to real sounds. So, for them, the neural signals from real and imagined sounds can overlap in the brain, potentially explaining the confusion.

David Kroop
West Friendship, Maryland, US
If you are a musician, you probably have hundreds of songs stored in your head, complete with the recorded key for each, and all the solos and instrument sounds it was recorded with. If you are a music writer, you probably have the melody snippets and chord progressions stored there too.

The way it works is you hear a song you like (note that ones you don't like you forget immediately), then play it over and over again in your head, refining its details. After that, it is essentially a permanently stored song. So the tune is heard via the ear, stored in the mind and thereafter played back in the mind and perhaps sung, if you are so inclined.

If you are a musician, that playback will translate into the tune being recreated on the instrument(s) of choice. If you have perfect pitch – meaning you can hum middle C perfectly in tune with no other aid – then the memorised tune will also be in the proper key when played back on an instrument. I can hear a few notes from a song and immediately identify the song and play it back on the piano.

PHILIP CARDELLA/ALAMY

This week's new questions

Getting greedy **Greed has contributed to massive wealth inequality. What are its evolutionary and psychological bases? What good is greed?** ***Jane Monroe****, Arcata, California, US*

Figure of eight **Is it possible for a planet to orbit a binary star system in a figure of eight? And is it possible for such an orbit to be stable?** ***Keith Marshall****, London, UK*

What are the evolutionary benefits for people being greedy?

Tyre change

What are the pros and cons of using carbon dioxide in tyres?

Hillary Shaw
Newport, Shropshire, UK
There are around 1.7 billion motor vehicles in the world, from motorbikes to off-road large transporters (and this neglects some 1 billion pedal cycles, whose tyres are small). A minority of these vehicles have more than four tyres, some huge. So, let's say there are the equivalent of 8 billion car tyres, which are, on average, 0.2 × 0.2 metres in cross-section and 1.6 m in circumference, and these tyres are typically inflated to 2 atmospheres. So, tyres account for about 1 cubic kilometre of air.

CO_2 is 1.5 times as dense as air, so to achieve the same tyre pressure would take 0.7 cubic km of the gas. However, Earth's atmosphere has an "equivalent" volume of 4 million cubic km (if all its gases were at sea-level density) and has currently 427 parts per million CO_2, so that's around 1700 km^3 of CO_2 (at sea level density) in our atmosphere.

Worse, if you made drivers inflate their tyres with CO_2, they would have to drive more (to a filling point), and you would need an industry to extract, store and transport the gas. And as tyres lose pressure, their CO_2 would re-enter the atmosphere. Garages would love this; the planet would hate it.

John Davies
Lancaster, UK
Tyres are commonly inflated with compressed air, and for normal purposes, this is entirely adequate. But compressed air contains water vapour, which may condense into water in cold weather, or vaporise as the tyre heats up in use, changing the pressure. And oxygen gas is a smaller molecule than the nitrogen in air and can percolate through the tyre rubber

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Tom Gauld
for New Scientist

"Formula 1 teams use dry nitrogen to inflate their tyres, so that the pressure will be maintained and predictable"

so that it deflates, very slowly. Compressed air may be dried, but dry nitrogen is widely available stored in a cylinder and pure nitrogen gas will stay in the tyre longer. Formula 1 teams use dry nitrogen to inflate their tyres, so that the pressure will be maintained and predictable.

Carbon dioxide is also available in cylinders for carbonated drink machines that are small enough to carry in a bicycle saddlebag, yet with enough gas to reinflate a punctured tyre. But the carbon dioxide molecule is even smaller than the oxygen molecule and the tyre will deflate in a day or so.

Mike Clarke
Castle Hedingham, Essex, UK

Carbon dioxide offers no advantage over air, which is free and mostly readily available. Then, of course, there is the environmental impact of the inevitable leaks. I'm not sure how you get rid of all the air already in the tyre to start with either. I can't think of any pros. Air seems to work quite well.

I know you

Which animals can recognise individual people? Are there fish, reptiles or insects that can do this? (continued)

Kirsten Cameron
Eindhoven, The Netherlands

Growing up on a farm in New Zealand, I once had a pet lamb called Gorgeous George. After he grew up and was weaned, he went out with a mob of other newly weaned teenagers to make his way in the world.

One day, I was walking to the beach down one side of the riverbed beside our house. On the other side of the riverbed, the shepherd went past with a mob of sheep. All of a sudden, one of the sheep came running out, baaing away, over to me. I stood frozen, thinking what on earth is going on! As this sheep got to me, I realised it was George! Reunited, I stood patting him as the shepherd kept going with the other sheep.

With George refusing to leave me, my sisters continued on to the beach and I walked back home and put him in the front paddock with Mum's black sheep – she had decided to take up spinning and knitting so had got some black sheep and was breeding them, getting them shorn, spinning the wool herself and then knitting jumpers.

Anyway, I put George in there with them. He lived his days out there – I remember often coming home from school and calling him over and saying hello to him. Every now and then, I had to walk him down to the shearing shed to get shorn.

Of course, the reality is that he probably didn't live his days out there – or rather his days may have ended a bit sooner than I admit – but in my head he did. ▮

Answers

Quick quiz #331 *Answer*

1 Iran
2 A mosquito's proboscis
3 Epstein-Barr
4 The Oort cloud
5 Gemini 3

Quick crossword #197 *Answers*

ACROSS 1 Wastage, **5** Gasohol, **9** Swift, **10** Trapezium, **11** Wii, **12** Ninth, **13** Motor, **14** GIGO, **15** Floppy disc, **19** Bombardier, **20** Floc, **22** Solve, **24** Zooid, **26** Gar, **27** Urticaria, **29** Bacon, **30** Hashtag, **31** Regular

DOWN 1 WYSIWYG, **2** Spirit gum, **3** Actin, **4** Entangled, **5** Graph, **6** See, **7** Hoist, **8** Lamarck, **13** Mayo, **16** Pterosaur, **17** Illogical, **18** Wave, **19** Bismuth, **21** Coroner, **23** Lotus, **24** Zero G, **25** Debug, **28** Cwt

#101 Knight's progress *Solution*

After each move, the knight rests on the opposite colour square to the one it came from. So, starting on a black square, after three moves it must be on a white square. The probability of it being on a black square is 0.

The top-right black square requires the knight to make a minimum of six moves, which is the highest number for any square.

After four moves, the knight can be on any black square other than the top-right corner square. So it can be on (64/2) – 1, or 31 possible squares.

Locked out

The phrase "you couldn't make it up", Feedback feels, is often misunderstood. It doesn't mean there are limits to the imagination, but rather that there are some developments you can't include in a fictional story because people would say "oh come on, that would never happen". The trouble is, those people are wrong, because real life is frequently ridiculous.

In the world of codes and ciphers, one of the more important organisations is the International Association for Cryptologic Research, described as "a non-profit organization devoted to supporting the promotion of the science of cryptology". The IACR recently held elections to choose new officers and directors and to tweak its bylaws. Being cryptographers, they did so in a clever way: they used Helios, an online platform that promises "verifiable online elections".

Helios is really quite clever. Every vote is tracked, so you can check that yours has been received and that it hasn't been altered – apparently making tampering impossible. At the same time, each vote is completely secret. The system "uses advanced cryptographic techniques to combine all of the encrypted votes into an encrypted tally, and only the tally is decrypted".

But how does the tally get decrypted, you may ask? Well, an organisation must designate a number of trustees. The IACR picked three, each of whom was given one-third of the cryptographic key. To decrypt the tally and see the results, all three trustees had to input their bit of the key. This was an all-or-nothing process: one or two bits of the key wouldn't get you even a partial decrypt.

And so, the inevitable happened. "Unfortunately, one of the three trustees has irretrievably lost their private key, an honest but unfortunate human mistake, and therefore cannot compute their decryption share," wrote the IACR on 21 November. "As a result, Helios is unable to complete the decryption process, and it is technically impossible for us to obtain or verify the final outcome of this election."

The IACR has had to void the election and start the whole process again. This time, it says, "we will adopt a 2-out-of-3 threshold mechanism for the management of private keys, and we will circulate a clear written procedure for all trustees to follow before and during the election". Feedback is keen to examine that "clear written procedure", if only to find out whether the first page reads "DON'T LOSE IT" in massive bold type.

We are also fascinated by the capacity of what the IACR calls a "human mistake" to cut through even the most ingeniously designed system. Every time some Silicon Valley hype-man tells us that human-level artificial intelligence is imminent, we groan inwardly, because the first human-level artificial intelligence will presumably be on a par with the average person – and, well, have you met people?

Twisteddoodles *for New Scientist*

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Float like a raisin

The capacity of science journalists to come up with new and interesting units of measurement never ceases to amaze. On 17 November, *The New York Times* ran a story about "a tiny solar-powered radio tag that weighs just 60 milligrams and sells for $200", which entomologists are using to track monarch butterflies on their migrations across North America.

Anthony Weaver flagged a sentence that tried to convey how much a tag weighs compared with its porter: "Most monarchs weigh 500 to 600 milligrams, so each tag-bearing migrator making the transcontinental journey is, by weight, equivalent to a half-raisin carrying three uncooked grains of rice."

Feedback thinks we can all agree this makes it much clearer, in a way that saying "about a tenth of your body weight" just wouldn't achieve. Or, as Anthony says: "As I picture myself as a half raisin on a transcontinental journey, carrying rice to Mexico, I finally understand firsthand how butterflies feel about science."

No, this isn't an invitation to send in similar examples from the pages of *New Scientist*. Don't even think about it.

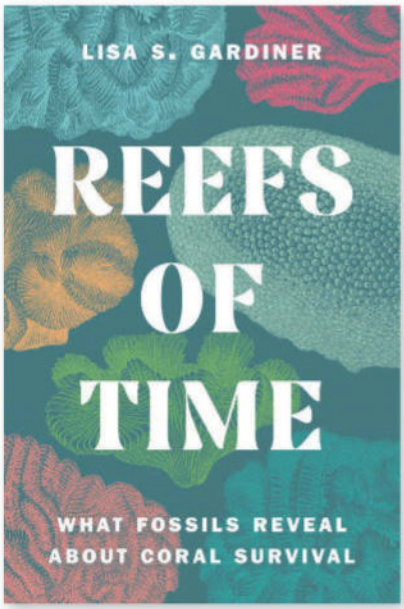
The boys' club

Feedback isn't on social media because, quite frankly, we don't have the mental energy to work out how to get eyeballs on half a dozen distinct sites that all use radically different algorithms. Nevertheless, we do keep half an eye on things, so we were intrigued to learn of an impromptu experiment on LinkedIn. Women on the site changed their names and pronouns to appear male, then saw their engagement rocket.

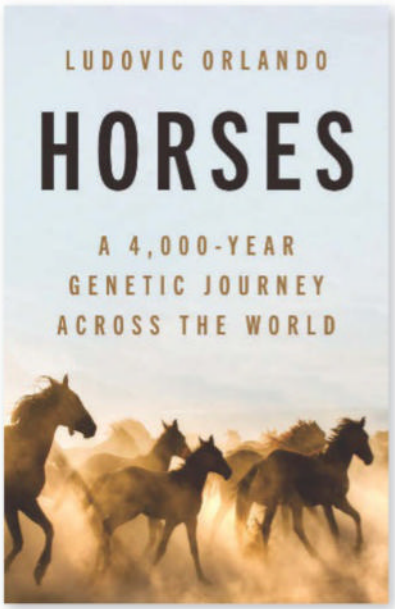
For instance, social media consultant Simone Bonnett changed her pronouns to "he/him" and her name to "Simon E", then saw her profile views increase by 1600 per cent, according to *The Guardian*. Others saw similar spikes. As a control, Daniel Hires, who incidentally has the perfect LinkedIn name, tried the opposite. "I changed my name to Daniela for 4 days," he wrote. "The result? Day 1: reach down -26%".

Now, Feedback must tell you that, according to LinkedIn's Sakshi Jain, the site's "algorithm and AI systems do not use demographic information (such as age, race, or gender) as a signal to determine the visibility of content, profile, or posts in the Feed". We don't doubt it, but we also thought that unintentional emergent effects were a major driver of algorithmic bias.

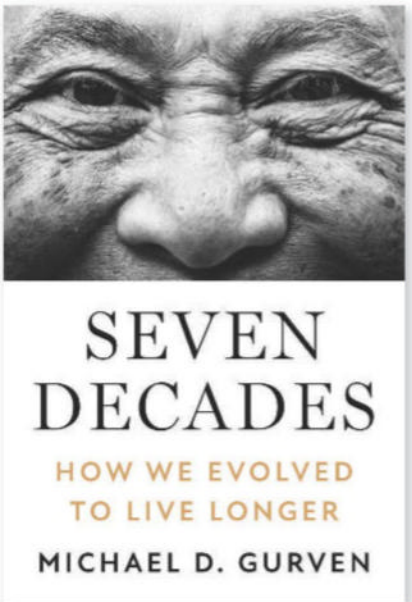
Meanwhile, Feedback is in the process of setting up our brand-new LinkedIn page. We're going to call ourselves Mansplain.



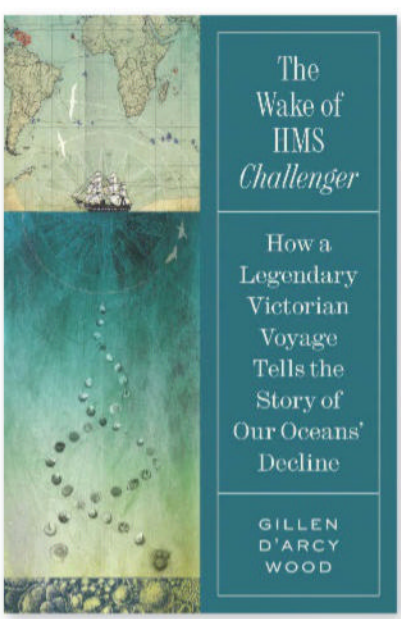
How fossilized reefs hold clues to the survival of corals in the Anthropocene



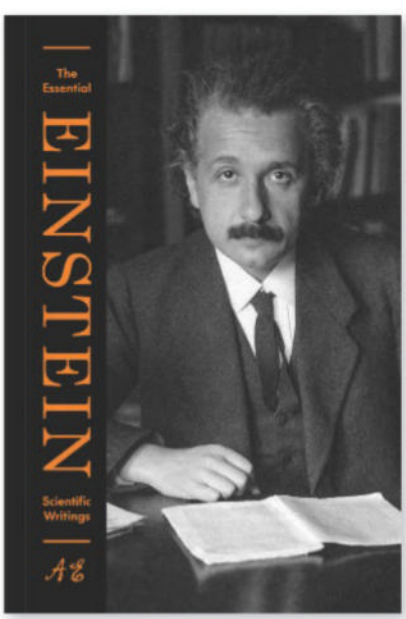
From one of today's leading experts on ancient DNA, a sweeping genetic history that unravels the mystery of where horses were first domesticated

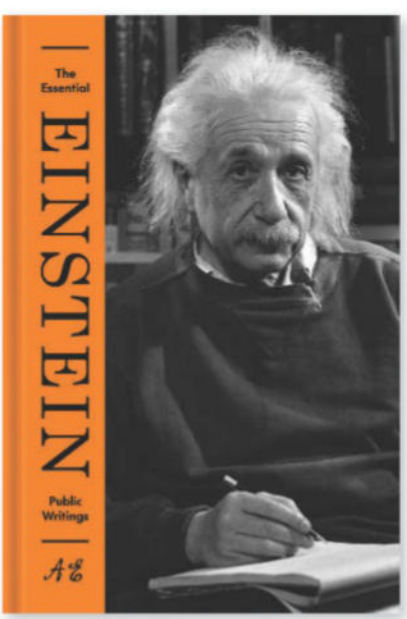


An anthropologist uncovers new evidence for the evolutionary origins of human longevity



A scientific adventure story that dramatizes how profoundly our oceans have changed over the past 150 years





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