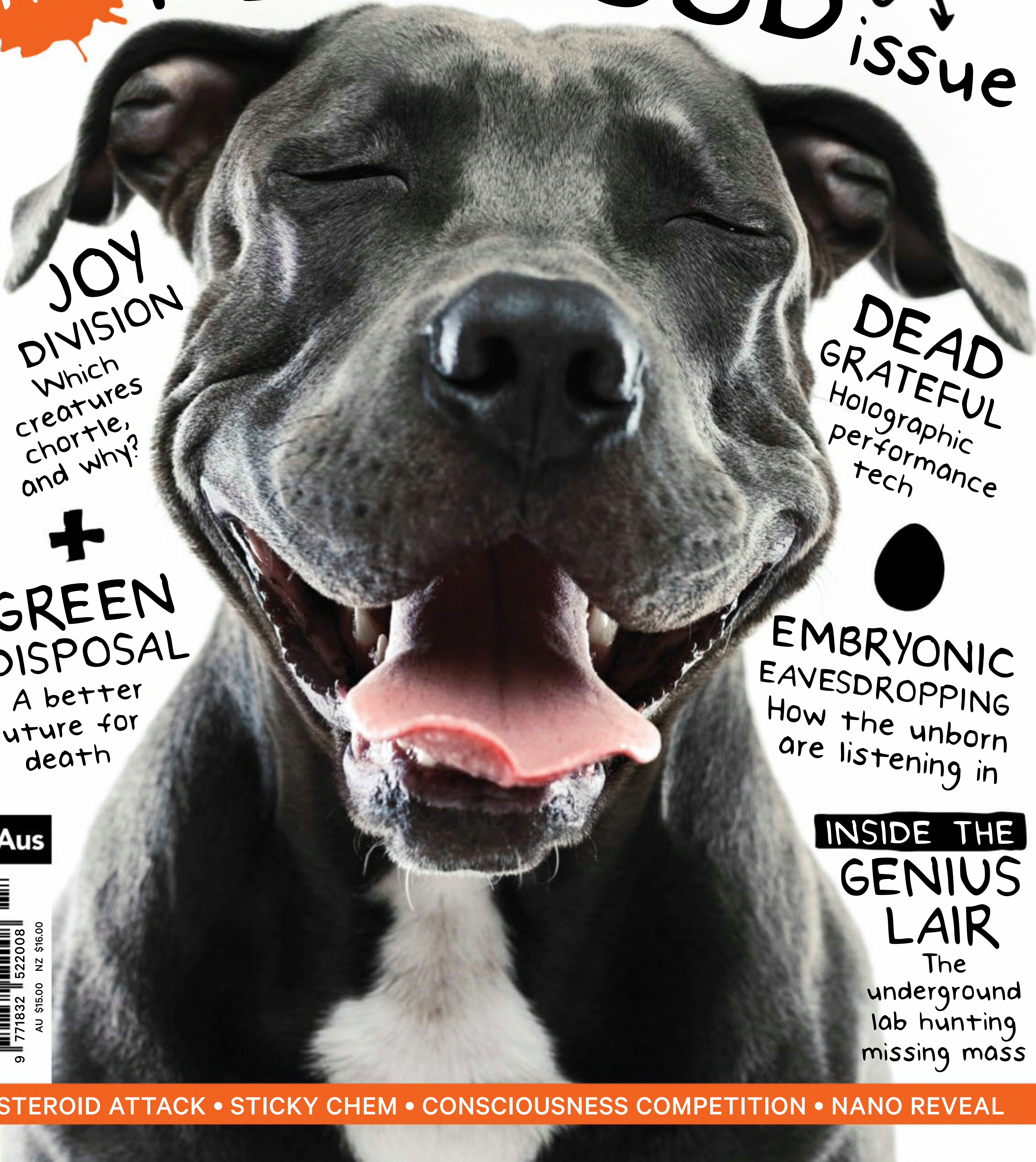
THE AUSTRALIAN TIME-TRAVEL EXPERIMENT AIMING TO REWRITE PHYSICS

COSMOS

HOW THE SCIENCE OF EVERYTHING MAKES EVERYTHING BETTER Issue 94

The FEEL GOOD issue



JOY DIVISION
Which creatures chortle, and why?

+ GREEN DISPOSAL
A better future for death

DEAD GRATEFUL
Holographic performance tech

EMBRYONIC EAVESDROPPING
How the unborn are listening in

INSIDE THE GENIUS LAIR
The underground lab hunting missing mass

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ASTEROID ATTACK • STICKY CHEM • CONSCIOUSNESS COMPETITION • NANO REVEAL


12:01

Big ideas; teeny blocks

How do you illustrate a story about a physics-breaking theory of time travel that's being experimentally tested in a security-restricted nuclear facility? With Lego, of course. One of this issue's favourite scientists, timelord Michael Wouters, has endeared himself forever (in both matter and anti-matter realities) with this rendition of the caesium clock set-up, complete with ANSTO's nuclear reactor (at right, blue; not to scale) and bonus scientist. To read more about this mind-bending theory – and its time-bending test – turn to page 42.

MICHAEL WOUTERS

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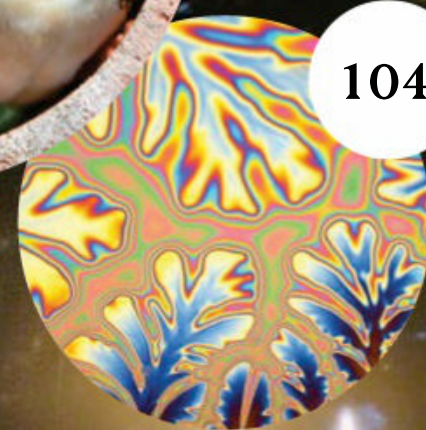

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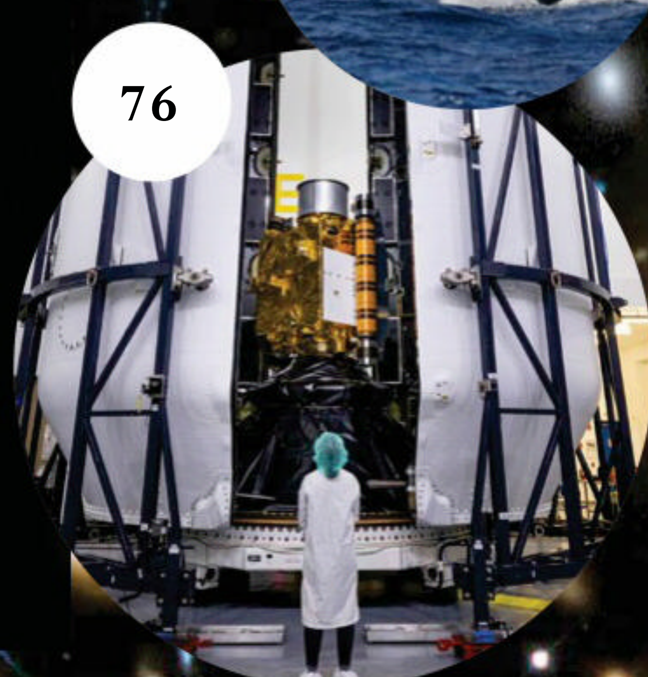

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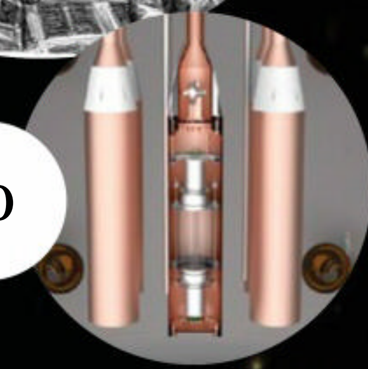

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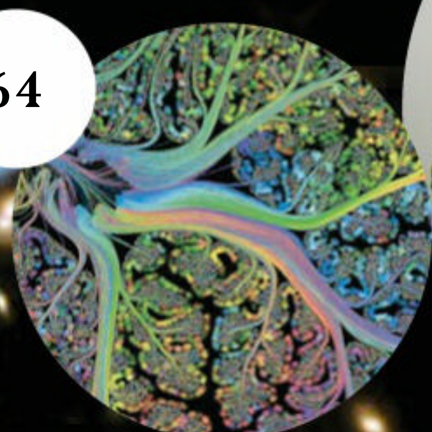

Gravitational lensing occurs when a large mass bends the light of background objects – as is happening here with the galaxy cluster MACS J0717, which lenses the largest areas of space we can see from Earth. Lensing also shows the existence of dark matter. Read more about the hunt for this elusive material on page 30.

From the Executive Director

IT SEEMS TO BE AN INNATE QUALITY of all of us that we look at aspects of our world and ask, "why" or "how". We are born innately curious. This curiosity is at the heart of all discovery. It is the impetus of science. Science is merely the method by which we gain the confidence that the answers to our curiosity are beyond reliable. Not all of us are scientists but all of us are discoverers.

It's why at the RiAus we are driven by the belief that not only do all people need well-communicated science in their lives, but they deserve these communications and want scientific facts and communications in their lives. Too often our media overlooks this value.

In the past 10 months, to expand and keep current the ways in which we communicate our excellent content, we've launched and operated a podcast service. These on-demand audio programs – written and presented by our splendid science journalists – are finding an excellent audience, which is not surprising that nearly all of us always travel with a sophisticated digital audio device in our pockets.

To better reach a wider audience we've recently partnered with the LiSTNR platform, Australia's leading curated podcasting platform, globally available, to co-produce and distribute new and innovative audio programs. With our content, science will become an important pillar of this popular media platform. You can find out more at cosmosmagazine.com. We hope that enjoy this extra way of engaging your curiosity and need to discover.

WILL BERRYMAN, Executive Director, Royal Institution of Australia

Science in the wild

Cosmos isn't just in print; our website produces daily news stories; we're expanding podcasts (see above) and occasionally we sneak out of the office to go behind the scenes of science around Australia. This year we'll be producing videos about some of the places using science to improve our lives. One we've visited already (left) is the BioCina pharmaceutical manufacturing plant in Adelaide – a potential source of homegrown mRNA vaccines. To watch this video series, along with interviews with scientists about what's exciting them in their field, visit cosmosmagazine.com/cosmos-briefing

ABOUT THE ROYAL INSTITUTION OF AUSTRALIA

The Royal Institution of Australia is an independent charity dedicated to connecting people with the world of science. Through *Cosmos* magazine, our free daily science news site cosmosmagazine.com, our e-publication Cosmos Weekly and free educational resources, we aim to be an inspirational resource centre for the wonders and achievements of Australian and the world's scientific discoveries. We want to spark in all people a desire to be science literate and to make informed decisions about their lives based on rigorously sought and tested evidence.

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From the Editors

IN TIMES GONE BY, periods of austerity ended – at least for bookkeepers – with the lid being screwed down on the red ink, and a nice fresh bottle of black or blue ink opened. Late summer 2022 feels a little that way. We're not yet out of the COVID woods, but somehow it seems like the tide's turned for better times, and we're feeling good about it.

This issue, join Jacinta Bowler on a dive underground to visit the 'genius lair' – aka the Stawell Underground Physics Laboratory (SUPL): a dark-matter detector in a disused goldmine beneath a town in country Victoria.

With guidance from a well-humoured band of biologists, Jamie Seidel takes a look at the animal species thought to enjoy a laugh. There's a funny side to being a lab rat? From mirthful mammals to the (barely) visible, Mark Pesce delves into the world of trying to see tiny things, and an accidental discovery in a Melbourne Uni lab that's led to an innovative startup.

And to the wildly, wonderfully theoretical: Lauren Fuge explains the anything-but-conventional ideas of physicist Joan Vaccaro, which last year drove the most fascinating experiment imaginable (there are timelords – really).

As always, there's much more besides. Amanda Yeo explains how to build a holographic concert performance (both easier, and harder, than it seems); Richard A. Lovett takes aim at rogue asteroids with NASA's DART initiative; Manuela Callari considers better and more environmental ways of disposing of human remains; and J.P. O'Malley reveals the remarkable, years-long experimental competition designed to settle on a theory of human consciousness once and for all. We've also been spending the last few months answering life's big questions from readers around Australia, a few of which we've featured in this issue.

There's such joy in the fidget-wheel detail of science's quest to learn – like a puzzle game in real life, scientists are explorers, adventurers and detectives all at once, and through their work the sum of knowledge grows. If that doesn't make you feel good, who knows what will?

GAIL MacCALLUM Editor
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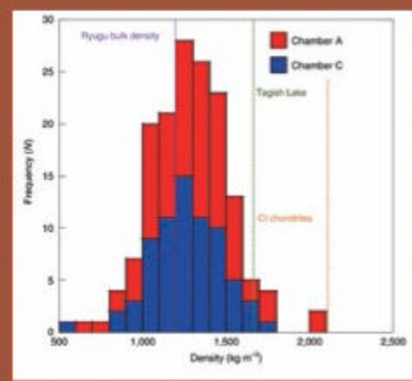
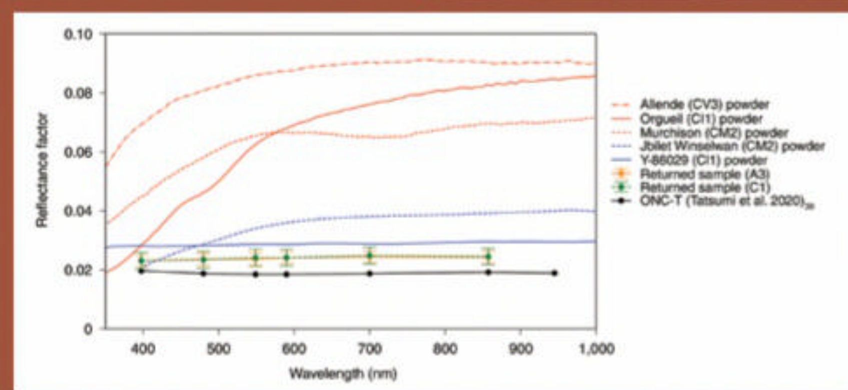
DIGEST

Science news from the around the globe

First results from Hayabusa's Ryugu asteroid sample

After a 5 billion km journey, Hayabusa's treasure hunt yields clues to the origin of Earth's water and organic material.





In December 2020, Japan's Hayabusa2 spacecraft dropped its treasure through the Earth's atmosphere and into the South Australian desert. This package held five grams of dust and rock from the primordial asteroid Ryugu (cover story, *Cosmos 88*).

Now, the results are in from the first preliminary analysis of this other-worldly material, and they show that we could soon discover whether asteroids like Ryugu brought water and organic materials to the ancient Earth.

Two studies – published in *Nature Astronomy* – delved into the physical properties and composition of Ryugu. Together, they confirm that it's a C-type asteroid – dark and rocky, rich in carbon and water. These types of asteroids are ancient, left over from the birth of our Solar System.

Scientists think that a type of meteorite known as carbonaceous chondrites, found on Earth, may have come from C-type asteroids. These meteorites look like they have been altered by fluids, which could fit with what we already know about C-type asteroids – formed in the far reaches of the asteroid belt, they contain ice that could have melted and helped produced clay minerals and carbonates (salts).

"One of the aims of the Hayabusa2 mission was to investigate the link between C-type asteroids and carbonaceous chondrites," explains planetary scientist Monica Grady. "This is important because carbonaceous chondrites are probably the sort of objects that brought water and organic compounds to Earth, enabling life to emerge here."

One study found that the sample was darker in colour than expected, reflecting just 2% of solar radiation, with a low density and a surprisingly high porosity.

The sample's density is also much lower than that of carbonaceous chondrites – perhaps because the meteorites that end up on Earth have to be hardy enough to survive a fiery plunge through the atmosphere.

"Ryugu may also contain more low-density material, such as organic molecules, than such meteorites," Grady adds. "This implies that the material from Ryugu has preserved a component of carbonaceous material that we have not been able to study before. This should allow us to learn more about the primordial building blocks of life."

The second study looked at the sample's composition, and found that it was rich in not only carbon but also hydrated minerals and clays, with a fine, uniform texture. This may suggest that Ryugu is the parent body of a type of meteorite called a CI chondrite – which give us a snapshot of what the Solar System was like when it formed.

According to Grady, together these papers "have shown us that the material from Ryugu is primitive and sufficiently different from known meteorites to make us think again about how representative meteorites are of asteroids. This might come to change some aspects of our view of early Solar System history."

Astronomers around the world are keen to learn more about these precious samples – and to compare them to a sample of the C-type asteroid Bennu, which will arrive back on Earth in 2023.

Hayabusa2's precious payload was retrieved from desert South Australia in December 2020. Now, first studies of the sample from the Ryugu asteroid confirm that it's an ancient C-type asteroid – a leftover from the Solar System's birth, formed about 4.5 billion years ago.

JAPAN AEROSPACE EXPLORATION AGENCY

RIGHT: NATURE ASTRONOMY

PALAEONTOLOGY

Fossilised dinosaur egg shows embryo preparing to hatch like a bird

An exquisitely preserved oviraptorosaur embryo suggests modern birds' pre-hatching behaviour originated with dinosaurs.

▲ A fossil found 20 years ago in Ganzhou, southern China, has been announced as an exceedingly rare, perfectly preserved fossilised dinosaur embryo. It was preparing to hatch in a distinctive "tucking" posture previously considered to be unique to birds.

LIDA XING

A perfectly preserved fossilised dinosaur embryo has been announced by Chinese scientists.

The embryo – named "Baby Yingliang" – was preparing to hatch from its egg in a distinctive "tucking" posture, previously considered to be unique to birds and never seen before in dinosaurs.

The ancient animal is an oviraptorosaur – a group of feathered theropod dinosaurs closely related to birds that lived during the Late Cretaceous period 100–66 million years ago. Theropods were a sub-group of obligate bipedal dinosaur with hollow bones and three-toed limbs, which also included *Tyrannosaurus rex*.

This discovery suggests that the modern birds' pre-hatching tucking behaviour could have evolved in dinosaur ancestors prior to the origin of birds.

Baby Yingliang is one of the most complete non-avian dinosaur embryos ever discovered, as most fossilised non-avian dinosaur embryos are incomplete and have disarticulated skeletons.

"We were surprised to see this embryo beautifully preserved inside a dinosaur egg, lying in a bird-like posture," says Waisum Ma from the University of Birmingham, UK, co-author of a study published in *Cell*. "This posture had not been recognised in non-avian dinosaurs before."

A modern bird embryo in the tucking position has its head placed under the right wing to stabilise it while using the beak to break out of the shell. The process is controlled by the central nervous system and is critical for hatching success.

Baby Yingliang's head is tucked between its arms and legs and its body is curled into a C-shape inside its egg. This has never been observed in articulated non-avian dinosaur embryos due to their scarcity.

The fossil was found in 2000 in Ganzhou, southern China, but ended up in storage until 10 years later, when it was unearthed during the construction of Yingliang Stone Nature History Museum.

The fossil was initially studied by scraping off part of the eggshell, but researchers say that they will continue to study it using various imaging techniques to gain insight into its internal anatomy.

BIOLOGY

60 MILLION ICEFISH NESTS FOUND IN ANTARCTICA

Massive fish breeding colony discovered in the chilly Weddell Sea.

Two thousand kilometres south of the southernmost tip of Latin America lies the Weddell Sea. These cold, iceberg-filled waters are home to krill, emperor penguins – and a massive breeding colony of icefish.

Cameras towed behind a German research vessel have spotted 60 million active fish nests across 240 square kilometres. This is the largest fish breeding colony yet discovered, and appears to be a globally unique ecosystem.

"A few dozen nests have been observed elsewhere in the Antarctic, but this find is orders of magnitude larger," says deep-sea biologist Autun Purser, lead author of a paper in *Current Biology*.

Known as Jonah's icefish (*Neopagetopsis ionah*), these fish are found exclusively in the Southern Ocean and live between 20 and 900 metres below the surface, preying on other fish and krill. They also likely provide input for local food webs, and may be the prey of Weddell seals.

FROM LEFT: AWI OFOBS. NAZAR ABBAS PHOTOGRAPHY / GETTY IMAGES

ENVIRONMENT

The science of wicket soil

What makes Australia such a good place to play cricket?

What makes a good soil for playing cricket – and why is so much work poured into getting the pitch right?

"Cricket wickets are a combination of science and art," says Jock Churchman, soil science expert from the University of Adelaide and the University of South Australia.

All sports played on turf have preferred soils for the activity, and plenty of work is done to maintain this soil. But cricket pitches, which play such a big role in the outcome of a match, present some of the most interesting and complicated soil science problems.

"In most sports, the main object of the soil is to provide good drainage," says Churchman. "But it's almost the opposite in cricket."

"It's got to be mouldable," says Churchman. "And it's got to be able to be flattened with rollers of course, and still maintain its integrity."

Finding a soil that is malleable enough when wet, but hard when dry, is a tricky task. Soils with high clay content are crucial, and in Australia, a particular type of clay called "swelling clay" is best.

"Swelling clay soil maintains its integrity," says Churchman. "It only cracks, it doesn't curl up. In other kinds of soil, when they dry, the particles curl up and that's not a good thing when you're trying to get a consistent bounce of the ball."

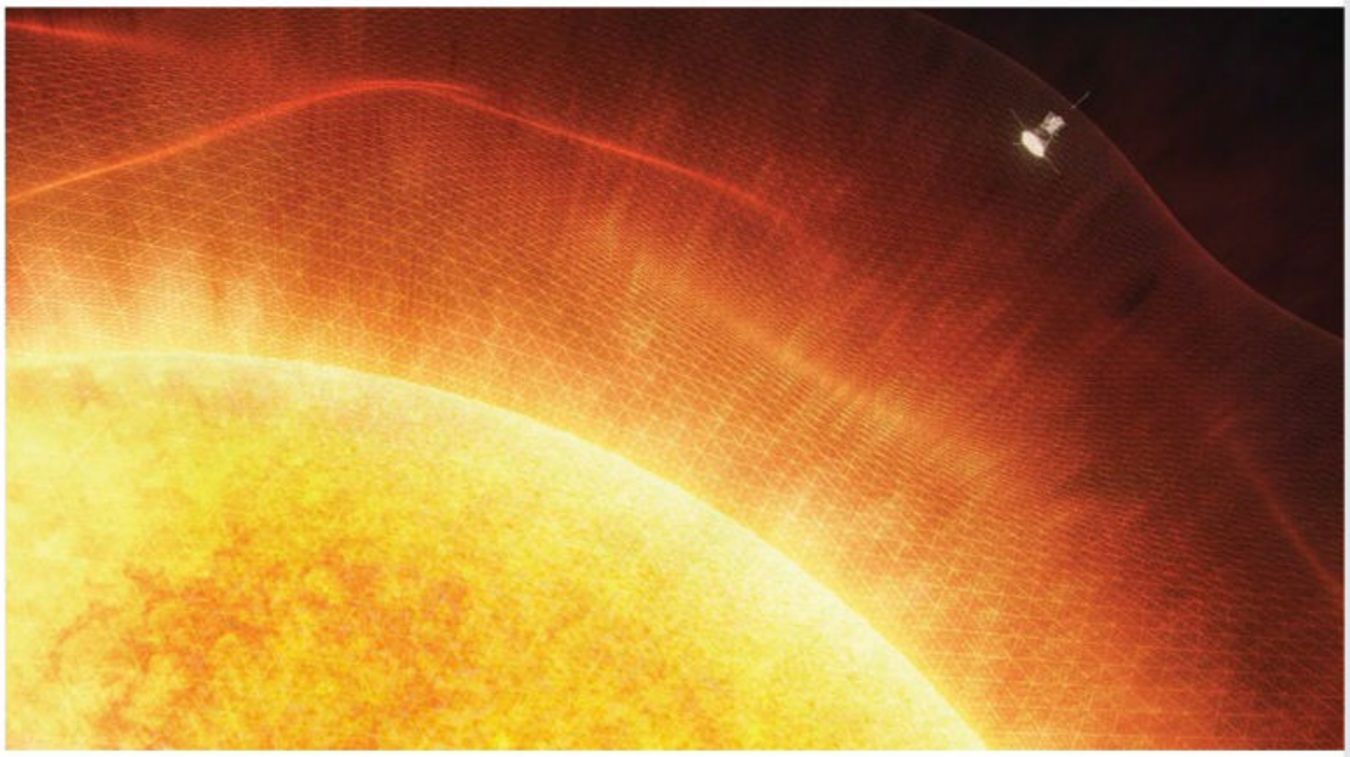
Swelling clay isn't as effective in damper climates like the UK and NZ.

With the drier climate in Australia, it leads to something of an advantage for our grounds.

SPACE

Parker Solar Probe becomes first spacecraft to touch the Sun

NASA probe has made humanity's first true visit to a star.



Launched in 2018, the Parker Solar Probe shot to fame as the fastest human-made object in history, reaching speeds of up to 700,000 km/h on its towards-the-Sun trajectory.

The Parker Solar Probe has done what was once thought impossible – touched the Sun.

NASA astrophysicists recently announced that on 28 April 2021, the spacecraft became the first to ever enter the Sun's outer atmosphere, the corona. This aura of blisteringly hot plasma extends for millions of kilometres out from the surface of the Sun itself. It's an extreme environment, with strong magnetic fields and temperatures of more than one million degrees Celsius – mysteriously much hotter than Sun's 5,500°C surface.

The probe spent five hours immersed in the corona's plasma, achieving the mission's primary objective. The measurements it made will lead to new insights about the physics of the corona and how solar wind forms.

The Sun's outer atmosphere truly begins at the Alfvén critical surface. In the corona, strong magnetic fields bind plasma and prevent solar wind from escaping, but at the Alfvén point, the solar winds can exceed a critical speed and blast off out through the Solar System towards interstellar space.

According to Gary Zank, a co-investigator on the probe's Solar Wind Electrons Alphas and Protons (SWEAP) instrument, it's "hard to overstate" the significance of what the Parker Solar Probe has now achieved.

"This event is what many heliophysicists have dreamed about for most of their careers," he says.

The probe will now descend deeper and deeper into the Sun's atmosphere and spend longer amounts of time there.

EARTH

THE LONGEST EVER LIGHTNING STRIKE

This new world record was no flash in a pan.

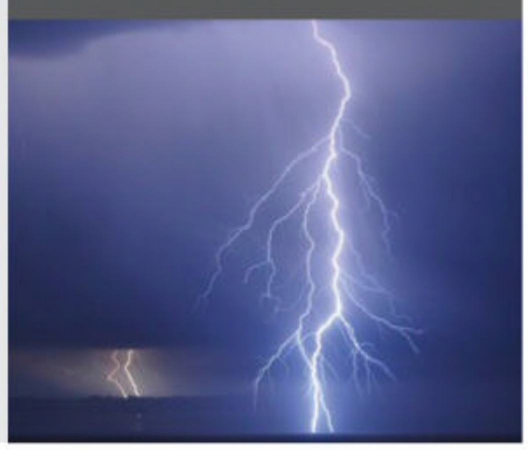
The World Meteorological Organisation (WMO) has announced its confirmation of the longest ever lightning strike, a gargantuan mega-bolt that stretched for more than 750km across three American states.

The flash actually occurred in April 2020, and was seen across a 768km stretch spanning Texas, Louisiana and Mississippi. This beat the previous record holder, a 2018 bolt in Brazil that stretched for 709km.

But how do you measure the length of a lightning bolt – a scientist with a measuring tape, running really fast?

Thankfully, no. The WMO was able to measure the mega-flash's length by using Geostationary Lightning Mappers (GLMs) on board the US National Oceanic and Atmospheric Administration's (NOAA) latest GOES-16/17 satellites.

The WMO also found a new candidate for the longest lightning flash by duration, a 17-second continuous burst over Uruguay and northern Argentina in June 2020.



FROM LEFT: NASA. DION THOMPSON PHOTOGRAPHY/GETTY IMAGES

▲ An ancient Homininae ancestor evolved strong resistance to snake-venom neurotoxins that's been passed down to some primates today. Those Homininae descendants with a lot more resistance – proportionately about 80% – include humans and gorillas (below left); the primates that missed out include orangutans (below right).

BIOLOGY

Toxic showdown: ancient primates vs venomous snakes

An ancient primate ancestor evolved resistance to snake venom – and passed it down to us!

Venomous cobras may not seem like snakes we should get up close and personal with, but an ancient Homininae ancestor of chimps, gorillas and humans evolved strong resistance to neurotoxins in snake venom – and passed it on to us.

But grandad Homininae didn't end up with resistance due to happenstance – it was part of an ongoing evolutionary arms race between African apes and deadly venomous snakes.

Over 10 million years ago – well before chimps and gorillas diverged but after orangutans did – grandad Homininae and friends were learning the lay of the land after coming down from the trees. He was picking up rocks, wandering around in shrubs, and waggling sticks. The problem was that these were also places frequented by venomous snakes, which could easily lead to a toxic bite or two.

And these neurotoxins are nasty.

"You can think of a particular type of neurotoxin like a heroin overdose," says study author Bryan Fry, molecular biologist at the University of Queensland. "You die of flaccid paralysis, because the diaphragm, the muscle that moves your lungs, doesn't move anymore.

"So, no movement of your lungs, no air. No air, no oxygen. No oxygen, no life."

According to the study, published in *BMC Biology*, the threat of venomous snakes appeared to be a driving force towards developing resistance to neurotoxins – after all, a Homininae that's remained alive after a snake bite is far more likely to pass on their genes than one that's dead.

"Our movement down from the trees to walk more commonly on land meant more interactions with venomous snakes, thus driving the evolutionary selection of this increased resistance," says Fry.

"It is important to note that this resistance is not absolute – we are not immune to cobra venom, just much less likely to die than other primates."

Interestingly, this resistance is still passed down to us today, meaning that we have proportionately 80% resistance – that's around five times more resistance than lots of other primates who didn't benefit from grandad Homininae's good genes.

Thanks grandad.

FROM TOP: DIKKYOESIN / GETTY IMAGES. WIKIMEDIA COMMONS

FOCUS: MEDICAL TECHNOLOGY

01

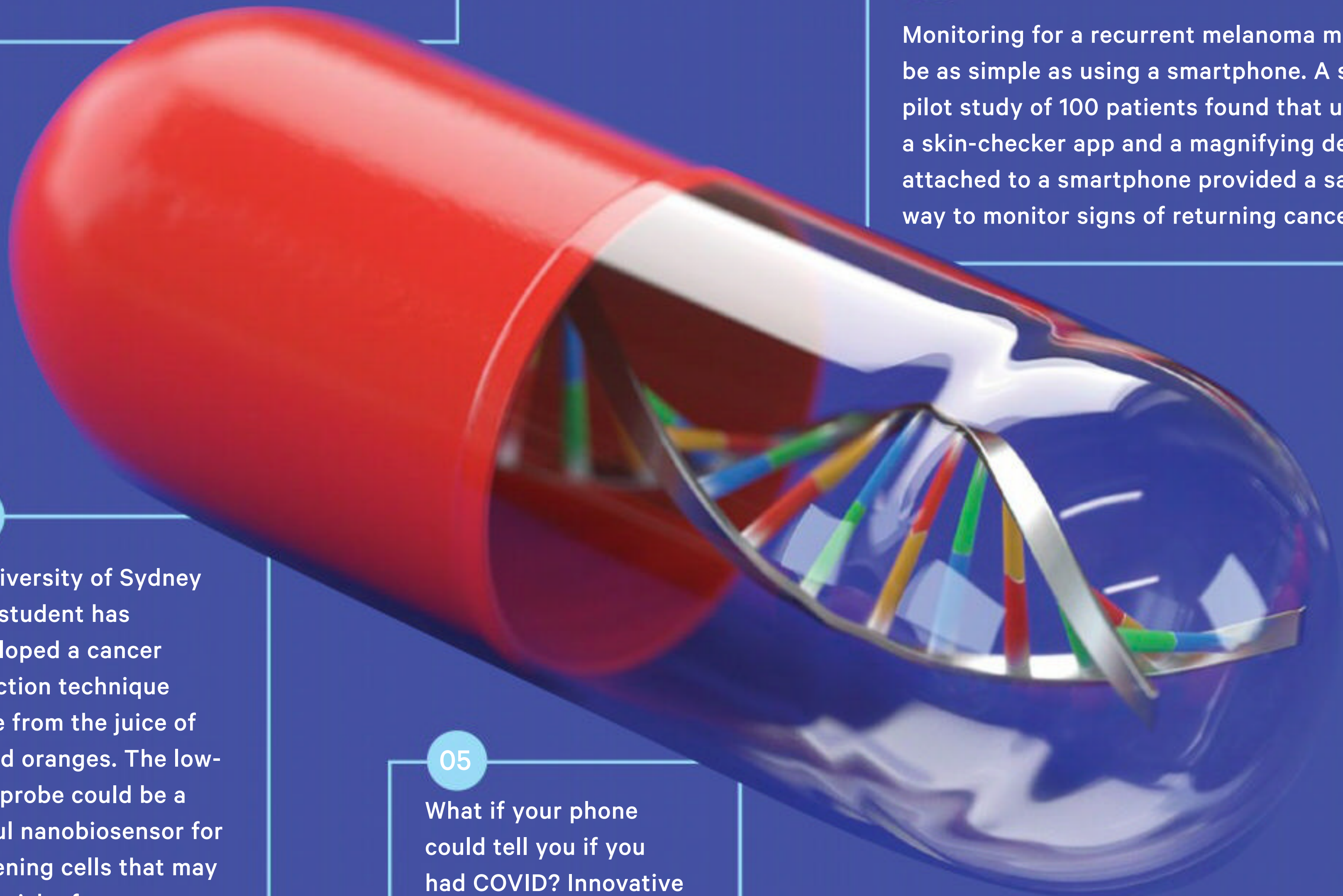
US researchers have developed a swallow-able mRNA capsule, which – in addition to paving the way for edible mRNA COVID vaccines, helping people with phobias of needles – could also help to treat gastrointestinal disorders.

02

A new AI system uses retinal scans taken during a routine visit to an optician to predict the risk of heart attack with 70–80% accuracy. This breakthrough could transform the way we screen for and track the early signs of heart disease.

03

Monitoring for a recurrent melanoma may be as simple as using a smartphone. A small pilot study of 100 patients found that using a skin-checker app and a magnifying device attached to a smartphone provided a safe way to monitor signs of returning cancer.



04

A University of Sydney PhD student has developed a cancer detection technique made from the juice of rancid oranges. The low-cost probe could be a useful nanobiosensor for screening cells that may be at risk of cancer.

05

What if your phone could tell you if you had COVID? Innovative research offers the promise of accurate testing for COVID and flu using chemistry and a smartphone.

06

A new microscopic camera system, the size of a grain of salt, can produce crisp, full-colour images that could help diagnose disease from inside the body.

www.cosmosmagazine.com/ **01** health/medicine/mrna-pills-vaccine-capsule-covid **02** technology/ai/the-eyes-are-a-window-into-heart-disease **03** health/body-and-mind/a-smart-way-to-monitor-melanoma **04** health/medicine/cancer-detection-with-oranges **05** health/covid/smart-lamp-smartphone-covid-test **06** technology/automation/microscopic-camera

BIOLOGY

GOOD BOY! DOG BRAINS UNDERSTAND DIFFERENCE BETWEEN SPANISH AND HUNGARIAN

New research shows canine comprehension of different languages.

In the first demonstration that a non-human brain can differentiate two languages, researchers at Eötvös Loránd University in Hungary have shown that dog brains can detect speech.

The brain imaging study – published in *NeuroImage* – trained 18 dogs to lie very still in a functional magnetic resonance imaging (fMRI) machine, where brain activity could be measured by detecting changes associated with blood flow. The dogs were then played excerpts of the Antoine de Saint-Exupéry classic *The Little Prince* in Spanish and Hungarian.

The results show that dog brains display different activity patterns in response to a familiar and unfamiliar language. They also found that dogs can distinguish between speech and non-speech – so your pup might know when you're talking nonsense.

EARTH

Why would you drop 27 seismometers on the ocean floor?

And now they're there… how do you get them back?

Near Macquarie Island in the Southern Ocean, a research vessel recently attempted to retrieve 27 seismometers from the sea floor to find out what drives earthquakes and tsunamis.

The research is part of a long-term project to learn about the undersea earthquakes and landslides that occur around the Macquarie Ridge – a subduction zone halfway between New Zealand and Antarctica – and how these tremors might affect coastal populations in Australia and New Zealand.

"In order to do that, we first need to understand the underground," says Hrvoje Tkalčić, from the Australian National University.

"The continuing waveforms that these instruments record will help us do that."

In October 2020, Tkalčić and colleagues journeyed to the remote island on the CSIRO research vessel *Investigator*. They dropped 27 seismometers on the ocean floor, some to depths below 5,000 metres, and deployed a further five on the island.

After 12 months of continuous data recording, the New Zealand research vessel *Tangaroa* returned to collect the seismometers.

They were connected to concrete ballasts when dropped, but these were fitted with a release mechanism. When instructed, the seismometers disconnected from the concrete and floated to the surface.

"We successfully recovered 15 out of 27 ocean bottom seismometers," says Tkalčić.

"As soon as we get the data, we will employ a comprehensive arsenal of seismic imaging techniques to understand the nature of the central Macquarie Ridge Complex and the associated earthquakes."

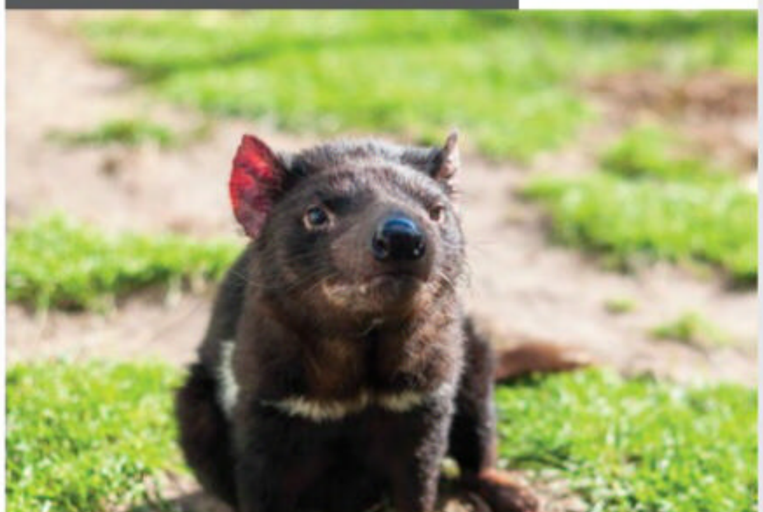
As for the 12 seismometers left behind, Tkalčić hopes for a tech billionaire to fund retrieval.

(DOG): ENIKŐ KUBINYI. (SHIP) COURTESY NIWA / JOSHUA MOUNTJOY.

BIOLOGY

TASMANIAN DEVILS PUZZLE SCIENCE WITH PICKY EATING HABITS

Our champion scavengers are creatures of taste, apparently.



Scavengers are known for their lack of discernment – they'll eat whatever they can find, whenever they can find it. But one Australian animal is breaking all the rules: the Tasmanian devil.

"We've found that most Tasmanian devils are actually picky and selective eaters," says Tracey Rogers, a professor at UNSW and senior author of a new study in *Ecology and Evolution*.

The study analysed eating habits of 71 devils from seven different sites in Tasmania using whisker samples, which carry chemical imprints of their diet.

It turns out that individual devils have their own tastes and preferences – much like us – and can be decidedly picky eaters, unlike other scavenger species like wolverines and hyenas. According to the researchers, this upends what we know about scavenger ecology.

PHYSICS

Quantum batteries a step closer with superabsorption breakthrough

Research gets us closer to super-fast charging batteries.

Quantum batteries are now closer to reality, with proof of the idea of superabsorption by an international team of researchers.

The discovery could pave the way for a class of batteries that charge faster the bigger they get – as well as being able to charge just from ambient light in a room.

"Superabsorption is the idea that the rate at which the light can be absorbed by the molecule actually increases as you increase the number of molecules," explains James Quach, a researcher at the University of Adelaide and lead author of a new study in *Science Advances*.

"This is a quantum collective effect."

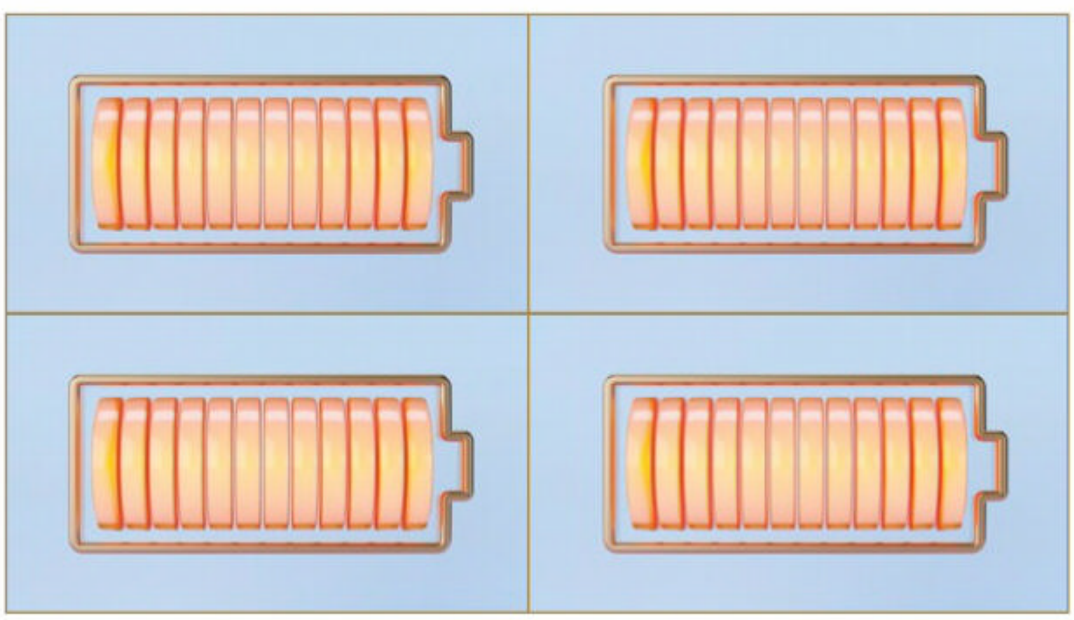
Superabsorption is key to the idea of quantum batteries. If molecules can absorb light at increasing speeds, they can be used to build quantum batteries which charge at increasing speeds.

"The more quantum batteries you had, the less time it would take to charge," Quach explains. Specifically, the time would be related to the square root of the number of batteries lined up together.

While superabsorption has been demonstrated with small numbers of atoms, this is the first example of the concept at a larger scale.

"For a long time, this was just a theoretical idea," says Quach. "We were the first to show this with organic molecules."

The researchers believe this discovery can be used to build a prototype of a rechargeable quantum battery.



FROM LEFT: XAVIER HOENNER PHOTOGRAPHY, ANDRIY ONUFRIYENKO / GETTY IMAGES.

▲ The 3.6-million-year-old Laetoli trackways in northern Tanzania, Africa, famously yielded the earliest evidence of hominin bipedalism. Another set of nearby footprints, long thought to belong to an upright bear, suggest another bipedal hominin ancestor was around at the same time.

CHEZBEATE / PIXABAY

ANTHROPOLOGY

Early footprints re-analysed as bipedal hominin's

It appears our early ancestors were more diverse than we thought, and co-existed with each other.

Around 3.6 million years ago in Laetoli, Northern Tanzania, a volcanic eruption spewed out ash and soot that came to settle in the plains below, thickening into a layer of mud for a few days. This would prove a boon for archaeologists millions of years later, thanks to the thousands of animal tracks found pressed into it.

Most famously, the Laetoli trackways produced the earliest evidence of bipedalism in hominins: a set of footprints discovered in the late 1970s belonging to *Australopithecus afarensis,* a hominin ancestor most famously known from the fossilised specimen called Lucy.

Now, a re-analysis of different footprints, long thought to have been laid down by an upright bear, has revealed they almost definitely belonged to another bipedal hominin ancestor – albeit one with a strange and shuffling gait. This study in *Nature* cements the reality that Africa 3.6 million years ago was populated by a far more diverse range of human ancestors than once thought.

"It's kind of odd," says Ellison McNutt, corresponding author and a PhD researcher in bipedal evolution. "It didn't quite match up with the fossils, which were admittedly few at the time; it's an unusual set of prints that had some interesting affinities with bears."

McNutt says since the original discovery of the prints in the 1970s, conventional wisdom now accepts that multiple hominins were moving across the landscape in the early days of our evolution. That's what compelled her and the research team to reinvestigate these strange, long-forgotten prints.

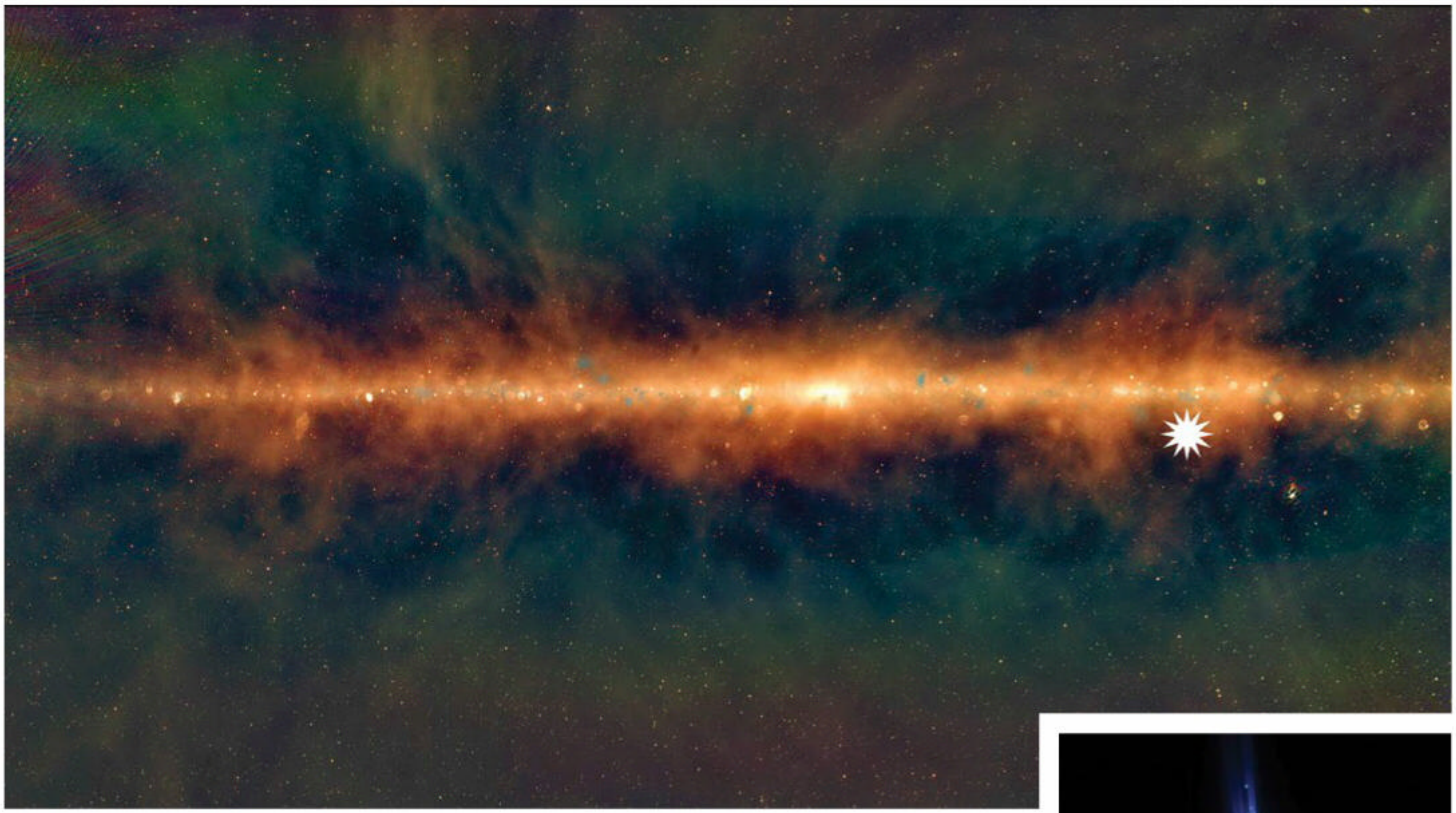
By studying the mechanics of bear movement, the team realised the prints could not have ursid origins, so they went back to re-excavate at Laetoli. They noted key features of the creature's anatomy, like the impression of the second toe, which disproved the bear theory once and for all.

But the prints were still highly unusual.

"These footprints display an example of what's called cross-stepping – it's sort of a catwalk where one foot goes all the way in front of the other," says McNutt.

"And that's a really interesting thing, because the ability to do that and remain standing requires some adaptations to your hip and your knee that humans have, but something like a bear or a chimpanzee can't do that."

What is clear from the multiple sets of hominin prints at Laetoli, all laid down within hours or days, is that ancient hominins were diverse and must have not only coexisted but interacted with one another.



ASTRONOMY

Mysterious object unlike anything astronomers have seen before

What to make of a newly discovered pulsing radiation source?

An Australian-led team scanning the cosmic melee for radio waves has discovered a mysterious object unlike anything astronomers have seen before. The object, GLEAM-XJ162759.5-523504, releases a giant burst of energy that crosses our line of sight and, roughly three times an hour, is one of the brightest radio sources in the sky.

"This object was appearing and disappearing over a few hours during our observations," says team leader Natasha Hurley-Walker of Curtin University. "It was kind of spooky for an astronomer because there's nothing known in the sky that does that."

Unfortunately, it's clear these signals aren't the work of little green men. The pulses of radiation come across a wide range of frequencies, which rules out an artificial signal, pointing instead to some kind of natural process we don't yet fully understand.

So far we know it's a radio transient, which are radio sources that switch on and off. This has left observing astronomers stumped because there's not enough observational data to understand what might have made the signal.

"That's a shame," Hurley-Walker says. "They're often going to come from very high energy processes in the universe.

▲ The star (top, at right) marks the newly discovered object in this radio-frequency image of the Milky Way from the Murchison Widefield Array. Above right: an artist's impression of what the object might look like.

"And being able to understand that would allow us to probe really extreme physics, like the intersection between quantum mechanics and general relativity."

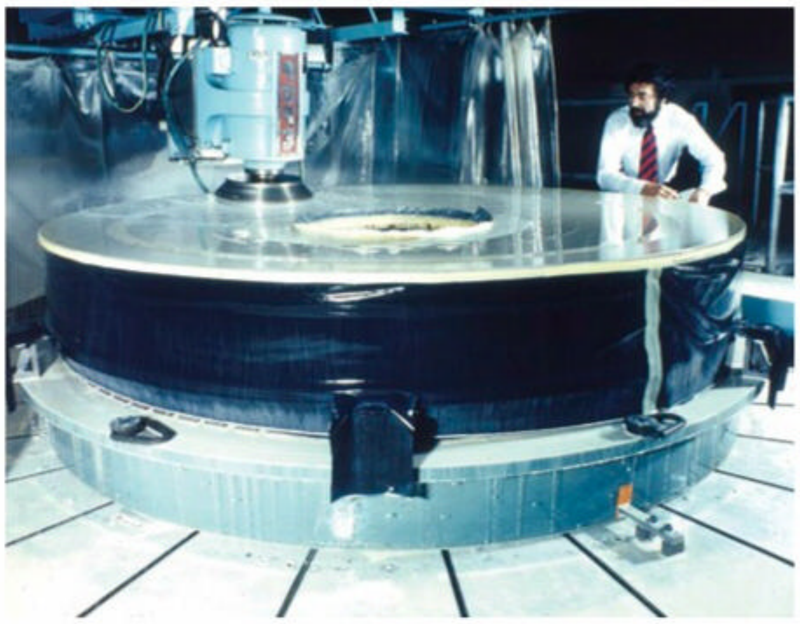
In this case, the team speculates this strange pattern of energy pulses is coming from a neutron star.

"What we think is that the magnetic field lines are somehow twisted and that this neutron star has undergone some kind of outburst or activity that is causing a temporary production of radio waves that makes it strong enough to produce something every 20 minutes," Hurley-Walker says.

It could also be a white dwarf, or it could be a cosmic object entirely new to science.

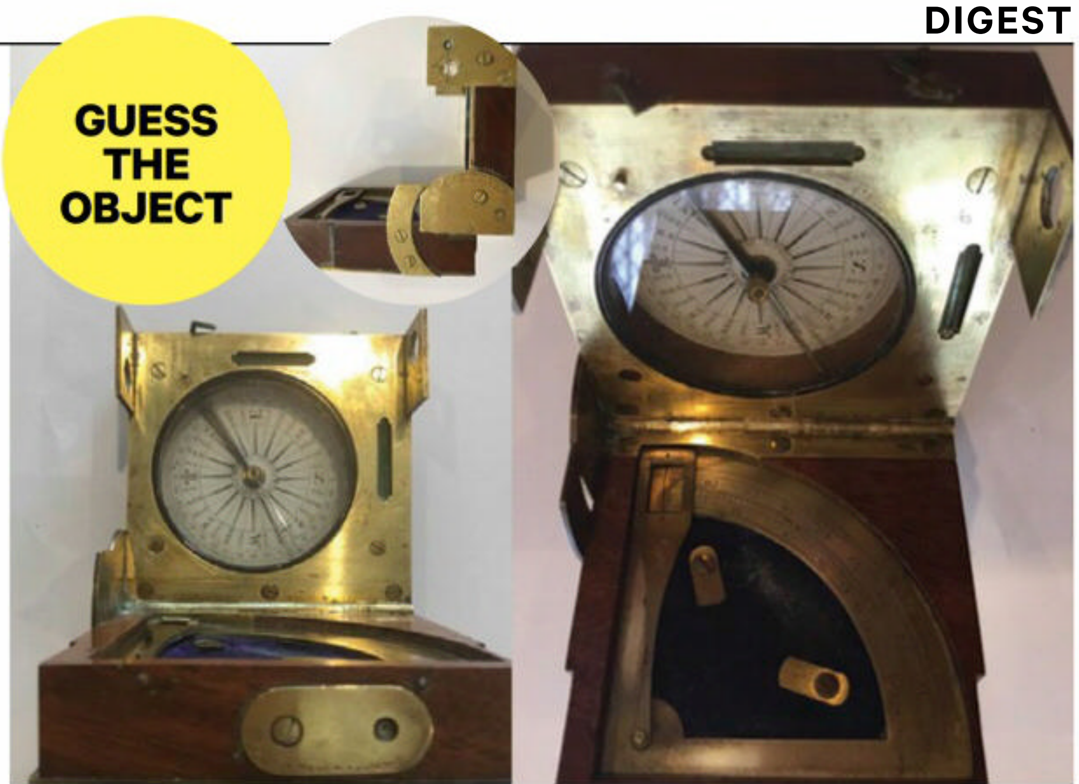
FROM TOP: NATASHA HURLEY-WALKER (ICRAR/CURTIN) AND THE GLEAM TEAM. ICRAR

The photo we titled "Disc-overy?" in last issue's GtO is the all-time leader for correct answers: yes, it's the main mirror of the Hubble Space Telescope getting its final polish. Those nailing it were led by Kym Markey (who must have emailed literally minutes after getting her copy of the magazine); followers included Matt in Brissy, Gabrielle Merten, Tim Sendall and Chris Jayne. Apologies to the dozen or more unmentioned – we're sorry we can't fit you all. And kudos to Andrew Stockley for the most creative response: "I think it's a CD of Wagner's Ring Cycle, the extended dance mix."



RIGHT: PRINT COLLECTOR / GETTY IMAGES

GUESS THE OBJECT



ALL POINTS QUESTION

Well here's some fun. This issue's object has been sent to us by a reader and he – and we! – genuinely don't know what it is. The pocket-sized object has been fabricated mainly from hardwood and brass and is embedded with a magnetic compass. The date of manufacture is unknown – it lives in a leather pouch that's marked 1906, but that could be when the pouch was made. It's sturdy and portable: 75mm x 75mm x 25mm (although you can bet its maker measured in inch increments). The Brisbane firm that made it shut in 1932; its long-time owner was J.C. James, of Armidale, NSW. Anyone who can identify it wins a copy of the book *Best Australian Science Writing*: write to us at contribute@cosmosmagazine.com

ENVIRONMENT

How to use drones responsibly in Kakadu

Indigenous-led guidelines are necessary for conservation technology.

Drones have transformed conservation and land management over the past decade, making it easier than ever to collect high-quality data. But like all new technologies, they come with new ethical quandaries – particularly when used on country managed by Indigenous Australians.

A group of researchers, Jawoyn traditional owners, and Indigenous rangers have addressed this by developing guidelines for responsible drone use in Kakadu National Park.

"We realised that there was a need to make sure that the drones were used in a way that ensured that traditional owners had control over when and where they were being used and how they could best benefit local people," says Jennifer Macdonald from Charles Darwin University and the CSIRO, lead author on a new paper in the *Journal of Responsible Innovation*.

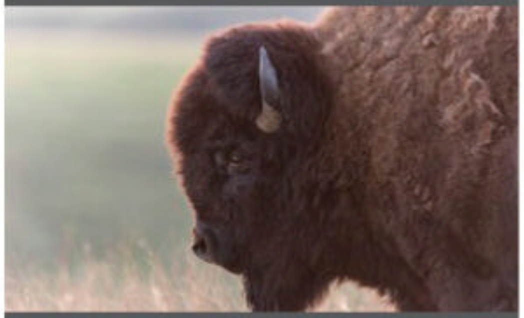
While drones can be a useful supplement to Indigenous land management, they can also be used disrespectfully and irresponsibly.

"There were some concerns raised about where the drones fly and the fact that they might be able to see some restricted sites, especially gendered sites," Macdonald says.

The protocols fall under three aims: empowering Indigenous governance, developing ethical and trusted research relationships, and enabling ongoing Indigenous-led technological innovation.

ARCHAEOLOGY

BISON SCIENTISTS UNCOVER 1,000-YEAR-OLD ROCK CARVINGS



Ancient archaeological find in Canada uncovered by wallowing bison.

Roaming bison in Canada's Wanuskewin Heritage Park have uncovered 1,000-year-old petroglyphs and the tool used to carve them, revealing the practices of ancient peoples in North America.

The heritage park is situated on the historic lands of the Dakota First Nation, and Northern Plains Indigenous Peoples, adjacent to the South Saskatchewan River.

"The discovery of these petroglyphs is a testament to just how sacred and important this land is," says Darlene Brander, CEO of Wanuskewin Heritage Park. "The individual who made these petroglyphs was actually carving their legacy into the rock many years ago."

The clever Saskatchewan bison were reintroduced to the park after more than 150 years, and their normal activity – including "wallowing" by rolling around in the grass to create dust pits – uncovered an embedded boulder that turned out to be a petroglyph.

FROM LEFT: BESTGREENSCREEN, COLLEEN GARA / GETTY IMAGES.

More megafires loom in Australia's future

Nine decades of fire data reveals we are increasingly in danger of widespread bushfires.

Australian bushfires are getting worse and it's being driven by climate change, according to a massive analysis of 90 years' worth of fire data.

Not only has the number of megafires in Australia spiked since 2000, but a greater expanse of land is being burnt, and they're happening more and more in autumn and winter. Even the cooler La Niña seasons don't offer much respite – in fact, the data shows that fires tend to be worse directly after La Niña years.

The researchers, led by the CSIRO's Pep Canadell, warn that we should prepare for another severe fire season in the summer of 2022/23.

"Our results really underscore the overwhelming role of climate change and associated changes of fire weather in driving the observed increased trends in burnt areas," says Canadell.

"Understanding these trends will help to inform emergency management, health, infrastructure, natural resource management and conservation."

Though we have always seen large fires in Australia, since 2000 the data shows that megafire seasons – where more than one million hectares of forests are burnt – have increased significantly. The study, published in *Nature Communications* and focusing on Australia's forests, found that of four forest megafires since 1930, three have happened since 2000.

Nine of the 11 biggest fire years, each with more than 50 million hectares burned, have also occurred since 2000.

The team found that from 1988 to 2018, Australian forests saw a 350% increase in burned areas – if the Black Summer fires of 2019/20 are included, that number jumps to 800%.

The cooler months don't even provide a break – since 1988, autumn fires have burnt three times more forest than previously, and winter fires have burnt five times more forest.

Forests are burning more frequently, too. There are now fewer years between them, with fire returning to the same area again and again.

"There are now regions in the southeast and south with fire intervals shorter than 20 years, preventing certain types of vegetation to reach maturity and therefore posing a risk to local ecosystem collapse," says Canadell.

▲ A study of nine decades of fire data shows that three of four megafire seasons since 1930, and nine of the 11 biggest fire years overall, have occurred since 2000.

ANDREW MERRY / GETTY IMAGES

MARINE BIOLOGY

Three separate attacks are the first confirmed blue whale deaths by killer whales

Australian researchers report the first documented killing of an adult blue whale by orcas.

For the first time, researchers have watched killer whales hunt and kill the largest animal on earth – an adult blue whale.

In late March 2019, annual whale and dolphin research surveys led by WA's Cetacean Research Centre (CETREC WA), along with Project ORCA, stumbled across the first-ever documented attack and eventual killing of a healthy adult blue whale (*Balaenoptera musculus*) by killer whales (*Orcinus orca*).

Reported in a paper recently published in *Marine Mammal Science*, there were also two subsequent attacks: one on a blue whale calf two weeks later, and one on a juvenile in 2021. Killer whales are known to prey on a large variety of species – including whales – but had previously only been known to kill and feed on large whale calves, such as grey and humpback whales. They have been seen attacking and harassing blue whales, but these events are the first confirmed kills.

"When we arrived, about 14 killer whales were attacking the blue in 70m waters, with the female killer whales leading the attack," says co-author Isabella Reeves, a Flinders University PhD candidate who witnesssed the first event. "We already noticed a substantial flesh wound on the top of its head with bone exposed. The dorsal fin was missing, no doubt bitten off by the killer whales."

Lead author and CETREC researcher John Totterdell adds: "Soon after, there was large chunks of skin and blubber stripped off the sides of the whale, the blue was bleeding profusely and was weakening, evident by its slow speed."

A female killer whale then lunged into the whale's mouth to feed on the tongue.

"After the whale carcass sunk, about 50 killer whales were in the area feasting and sharing around the blue's flesh," Totterdell concludes.

▲ In 2019, killer whales were for the first time observed hunting and killing a healthy adult blue whale. Killer whales have significant influence on the marine ecosystem, but relatively little is known of their behaviour in Australian waters.

JADE SHARP / WHALE WATCH WESTERN AUSTRALIA

CHEMISTRY

THE DOUBLE-THREAT COPPER SURFACE THAT KILLS BACTERIA IN MINUTES

Australian nanotechnologists are mounting a new challenge to antibiotic resistance.

The newest warrior in the fight against antibiotic resistance may come with a copper shield. A team of nanotechnologists has developed a copper-based substance that kills more than 99.99% of bacteria on it within a couple of minutes.

Copper has long been known for its antimicrobial properties, but it's usually fairly slow-acting: an ordinary copper surface can kill around 97% of *Staphylococcus aureus* (golden staph) in roughly four hours.

This new copper surface, described in a paper in *Biomaterials*, can kill more than 99.99% of the same bacteria within two minutes, which means it could be highly effective against strains of bacteria that are resistant to antibiotics.

The team hopes it can be used as an antimicrobial surface on doorhandles and other high-touch surfaces in hospitals, schools and public spaces, or in face masks and air filters.

RENEWABLES

Risks and rewards of aluminium in solar panels

Aluminium could become a big PV polluter, but it's also easy to recycle.

As the price of solar power plummets, the uptake of solar panels and rooftop solar is booming, which will make it easier to mitigate climate change.

But the materials and processes needed to build solar panels (or PV, photovoltaics) are not carbon-free. Research from the University of New South Wales (UNSW) points out that the aluminium in solar panels will need to be made sustainably to minimise panels' emissions.

"Lots of people get focussed on silicon, and they talk about the silver," says Alison Lennon, a UNSW researcher and chief scientist at Sundrive Solar.

"But when you actually install a PV system, the modules have got to have frames. And then you've got to put the modules onto the roof, and often there's a tilt, and there's a lot of aluminium that goes in all that railing."

Other parts of the kit, such as the casings for inverters, are also often best made with lightweight, waterproof aluminium.

Unlike the case for more precious metals, there isn't a predicted shortage of aluminium. But the researchers caution that aluminium needs to be found and purified in more sustainable ways than it currently is.

"There's actually quite a lot of aluminium in the Earth's crust," says Lennon. "In Australia, we have enormous amounts of aluminium resources, or bauxite. It's more a matter of the global-warming potential of refining all that bauxite into aluminium, because it requires so much energy."

Currently, a lot of the world's bauxite is refined in China, using fossil-fuel power. Lennon says localised aluminium production, particularly in Australia, could be much less carbon-intensive.

FROM LEFT: SURATSADORN KRAJOMTHONG / EYEEM / GETTY IMAGES. WESTEND61 / GETTY IMAGES.

PALAEOBOTANY

INCREDIBLY RARE BOTANICAL EVENT CAPTURED IN AMBER

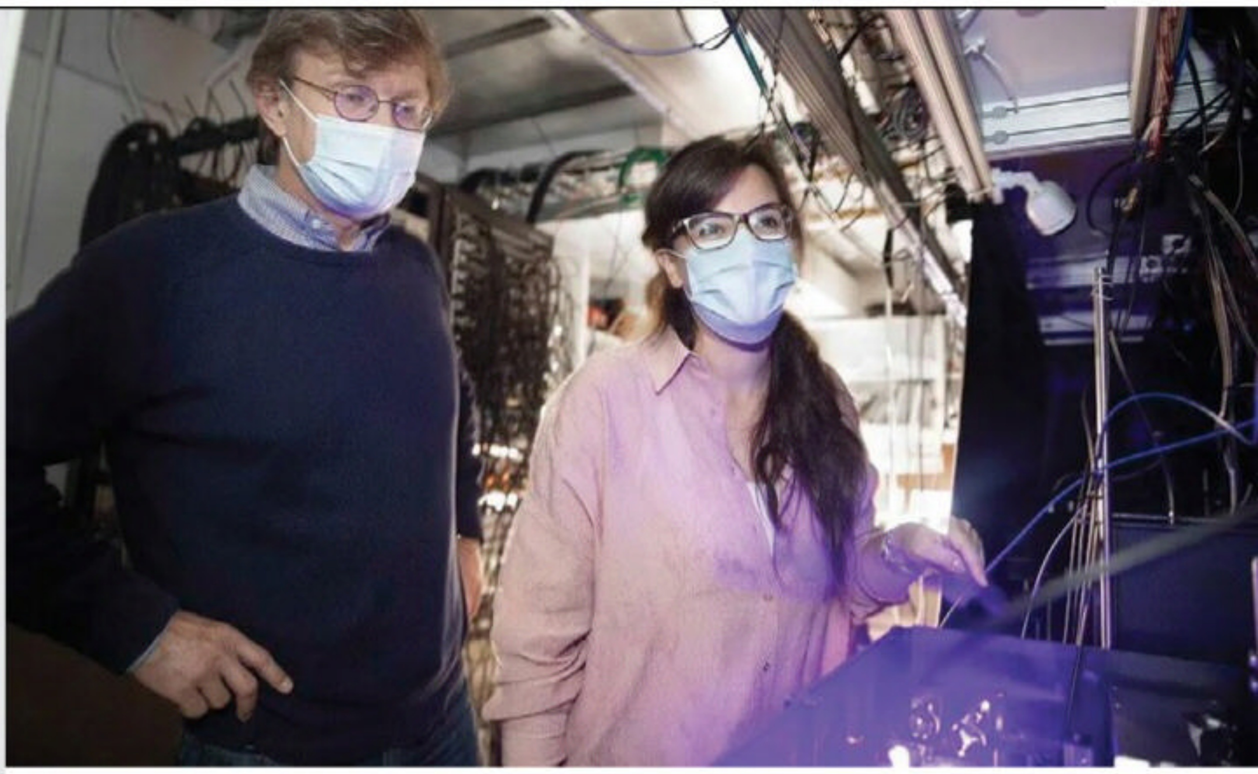
These entombed ancient sprouts pose intriguing questions for biologists.

The rare sight of 40 million-year-old seeds sprouting from a pinecone fossil has been found immortalised in amber.

This unusual method of development – called precocious germination – isn't common among plants in general and is almost unheard of in pines. The pinecone fossil provides the first evidence of the trait's extraordinary age.

"Crucial to the development of all plants, seed germination typically occurs in the ground after a seed has fallen," says palaeobotany expert George Poinar Jnr of Oregon State University, US. "We tend to associate viviparity – embryonic development while still inside the parent – with animals, and forget that it does sometimes occur in plants."

This is the first fossil of plant viviparity involving seed germination, but Poinar says it may have occurred hundreds of millions of years earlier.



PHYSICS

Quantum spin liquid observed in physics first

Researchers finally document never-seen-before state of matter.

After 50 years of hunting, physicists have finally observed a new state of matter known as a quantum spin liquid.

"It is a very special moment in the field," says physicist Mikhail Lukin, co-director of the Harvard Quantum Initiative (HQI) and a senior author on the study in *Science*. "You can really touch, poke and prod at this exotic state and manipulate it to understand its properties... It's a new state of matter that people have never been able to observe."

Quantum spin liquids were first theorised in 1973 and have been hotly sought-after because of their potential applications in quantum computing and high-temperature superconductivity.

Researchers led by Harvard University have finally experimentally documented this new state of matter.

They set out to find it using a programmable quantum simulator at the HQI lab. This is a special kind of quantum computer that can create shapes like squares, honeycombs or triangular lattices, which in turn can engineer various interactions between ultracold atoms. It allows researchers to reproduce physics on a quantum scale, study the complex processes that arise – and control them.

"You can move the atoms apart as far as you want, you can change the frequency of the laser light, you can really change the parameters of nature," explains co-author Subir Sachdev, also from Harvard University. "Here, you can look at each atom and see what it's doing."

The team used this simulator to create a quantum spin liquid, the properties of which could be key to creating qubits for quantum computers that aren't affected by noise or interference.

FROM LEFT GEORGE POINAR JR., OSU. KRIS SNIBBE / HARVARD STAFF PHOTOGRAPHER.

SPACE

Record scratch: maybe there actually IS liquid water on Mars?

There is, there isn't, there is, there isn't… what's the deal with liquid water on the red planet?

Grab some popcorn, because a study has recently argued that our strongest evidence for liquid water on the Mars is nothing more than a dusty mirage, shattering our most potent hope for discovering microbial life on the red planet.

The original evidence came from Italian researchers in 2018, who have now come back with a vengeance, doubling down on their conclusions that there actually is a sub-glacial liquid lake beneath Mars' south pole.

So, what's the deal? Is there liquid water on Mars or not?

Well, we know that Mars is covered in vast regions of ice, and that the planet used to host liquid water in the distant past, thanks to the impressions that rivers and oceans carved on its rocky surface billions of years ago.

But 2018 was the first time we had any strong evidence of liquid water on the planet in this day and age. The glint of possible sub-glacial water was glimpsed by the European Space Agency's Mars Express Orbiter.

The announcement fuelled hopes that we might, with a bit of focused exploration, one day find microbial life on Mars.

But in late January 2022, US researchers published a paper in *Geophysical Research Letters* that refuted the Italian team's original claims. They offered an alternate explanation for the shiny-bright signal underneath Mars' southern pole: they suggested it was a mirage caused by volcanic rock buried under the ice.

Meanwhile, the original team published a new study addressing alternate theories and doubling down on their initial conclusion. One major remaining question was how liquid water could persist in the frigid (-73°C) temperatures assumed to occur beneath the ice cap.

The team found that a group of salts commonly found in the Martian soil have anti-freeze properties, and so there could indeed be a briny, sub-glacial lake sloshing around underneath all that ice.

Though we don't yet know where we stand, it's exciting that this scientific back-and-forth inches us closer to the truth.

"Science isn't foolproof on the first try," says Isaac Smith, a Mars geophysicist who was not involved with the studies.

"That's especially true in planetary science where we're looking at places no one's ever visited and relying on instruments that sense everything remotely."

Is there liquid water on Mars? Most likely not at Mount Sharp (below), captured in this portrait by the Curiosity rover, but Italian researchers in 2018 thought yes at the Martian south pole. Those claims were refuted by a University of Austin, US, study earlier this year.

NASA / JPL-CALTECH / MSSS

A new view of distant galaxies

The James Webb space telescope is in position and, as Rebecca Allen explains, it promises a clearer view – and deeper understanding – of the origins of the cosmos.

Growing up under the clear night skies of the state of Georgia, in the south-east of the United States, I remember lying in the back of my dad's pickup truck looking up at the constellations, and even from that very early age of nine or 10 there was just something so fundamental and wonderful about seeing the Moon and the stars that just clicked in me – it was so inspirational.

Then I got my first telescope, and began the methodical process of looking at a map of the night sky, going out and observing it myself. The challenge of finding planets and observing meteor showers – that was my real start, identifying objects and recognising the patterns in the night sky.

When I was in early secondary school, astronomers confirmed that it was in fact a comet or an asteroid that had finished off the dinosaurs, because they found the crater in the Yucatan Peninsula of Mexico. That's when the real science questions kicked in for me. If an asteroid could do that to the dinosaurs, what about us? I really knew from that young age that I wanted to explore these types of questions, and that I wanted to study astronomy.

My first really serious interest was around black holes. They're mysterious objects in our universe that form after massive stars die, that reside at the centres of galaxies. I was fascinated by these extremely massive, dense objects – light can't escape from them, they break the laws of physics as we know them, but they're tied to these enormous systems like our home, the Milky Way galaxy. What's the relationship between a black hole's formation and the evolution of the galaxy around it? That's where I became fascinated with galaxy formation, and how it fits in with the greater picture of cosmology – the history of our universe.

Until very recently, we couldn't directly observe black holes, and we had to study their effects indirectly. It seemed like a natural question to pursue. How do black holes evolve? How are they such critical ingredients to a galaxy's evolution? How does that all connect over billions of years in the history of our universe? You start a PhD with what you think is a simple, straightforward question. And, of course, the more you investigate it, the more complex it is.

For my PhD, I was able to use the Fourstar Galaxy Evolution Survey, known as the ZFOURGE survey. It used days' worth of time on the Magellan telescope in Chile to stare at patches of sky to collect as much information as it could about distant galaxies. Using that ground-based survey gave us a sample of tens of thousands of galaxies, spanning across time all the way back to when the universe was just a billion years old. Now, it's 14 billion years old.

So you're getting information about a galaxy's mass, which is critical, and its components – what kind of stars make up the galaxy. Then, with the Hubble space telescope (HST), we were getting these incredible images in very high resolution, and we could measure galaxies' sizes and what we call their morphology. That was a

FROM LEFT: SWINBURNE UNIVERSITY. NASA.

The James Webb space telescope, locked and loaded for launch into space (main photos left and right, full-scale model below). It is currently being tested in its orbit, promising new insights into distant galaxies.

FROM LEFT: NASA / GODDARD SPACE FLIGHT CENTER / PAT IZZO. NASA / CHRIS GUNN

real "aha" moment, to be able to separate the different samples of galaxies.

All galaxies have their own properties – they're not all the same. Through these amazing telescopes we're learning that galaxies have their own kind of personalities. You can't just lump them all together. If we really want to understand how they grow and evolve, we have to appreciate all the different types of scenarios.

It's incredible to use these modern telescopes to capture the light of galaxies as they were in the very early universe. And that helps you build this entire kind of fossil record of galaxy evolution. We set out asking questions like, what is the growth rate of galaxies over time by measuring the extent of their starlight? Well, once you realise that some galaxies are forming stars actively, and some galaxies aren't, you have to kind of step back and ask yourself if it's fair to look at these galaxies in the same way.

Needless to say, there is still very much for us to learn, which is why I'm so excited about the recently launched James Webb space telescope (JWST). It will allow us to really pull back the curtain. Hubble was incredible, because it allowed us to see very distant galaxies for the first time. But the JWST's infrared observing capabilities mean we can take a step further back in time and perhaps image some of the very first galaxies.

We're used to seeing pictures of galaxies as gorgeous spirals, like the nearby Andromeda galaxy. But that's not what you see when you look to the early Universe – you see fuzzy little blobs. There are limitations on what information we can extract from those images. Now, with the JWST, we'll be able to see the details, the morphologies, of these early galaxies with even better resolution than Hubble.

Some fundamental assumptions have been shaken in the past few years, because astronomers have found galaxies that are older and bigger than we thought should exist at such early times. JWST will capture these more evolved galaxies that exist in the early universe and address a crucial question: how are we getting galaxies so massive and so mature at a stage when they shouldn't be quite there yet? It's going to have big implications for what we know about galaxy formation and evolution.

The James Webb space telescope is definitely the "next big thing" in astronomy. Hubble is in orbit, not too dissimilar to the International Space Station orbiting the Earth, which means we can service it – we've sent missions through the shuttle program to do so. But JWST is actually trailing behind the Earth, orbiting the Sun. So it's going to be much further away: almost 3000 times the distance of HST! Which is fantastic, because it'll be able to get these views of deep space like never before, but we will absolutely never be able to fix it if something goes wrong.

We're at the dawn of what's called "first light". As soon as the telescope can start taking scientific data, there are astronomers here in Australia who will be looking at these exciting questions around early galaxies in the distant universe.

DR REBECCA ALLEN is project leader for Swinburne University's Space Technology and Industry Institute.

Empowering our energy future

Australia has the resources to lead the world in battery production and – as Mahdokht Shaibani argues – if we did more than just export those raw materials, we could supercharge our economy.

In the country I come from, Iran, I found myself surrounded at an early age by successful engineers in my family and in society – in Iran there's actually a large proportion of people engaged in engineering disciplines. It was as clear as day to me that if I wanted to design something, bring about change, create something for the better, to have an impact in life, I should become an engineer. I did my undergraduate studies in materials engineering, which prepared me to become a battery engineer.

Things have changed fast in the battery world. About 10 years ago, the main idea of making a better battery was simply to make it more powerful – to make it last longer. But about five or six years ago, other criteria became extremely important: the idea of making batteries more sustainable, cleaner and more affordable.

Scientists had started to reveal more and more of the downsides – the dirty secrets, if you like – of the production of lithium-ion batteries.

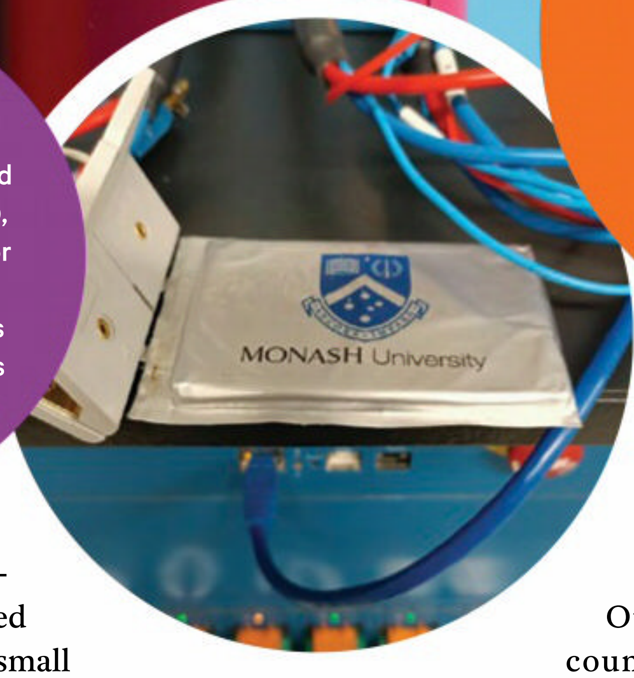
In fact, there have been lots of environmental and humanitarian issues related to mining for the materials that are required to make lithium-ion batteries. We might have thought that by driving an electric car we're not hurting our environment, but batteries have been produced by emitting carbon. Over the past few years, it's been important for me and for many in the industry to design batteries that are environmentally friendly in the materials that they use. Basically, we are trying to make low-carbon batteries.

I would say that the lithium-ion battery has proved its superiority for pretty much every application potential. It would be difficult to imagine that there would be a completely new battery chemistry that could compete with lithium-ion. There could be supporting battery technologies – lithium-sulphur batteries, for example, which is one of my areas of expertise. But these aren't going to be able to cover all of the applications that lithium-ion can accommodate. Lithium-ion is going to be here for quite a long time.

In fact, Australia is the largest producer in the world of lithium, contributing up to 50% of the world's lithium mine/concentrate. Plus we have large deposits of nickel and cobalt, which are the other critical ingredients for lithium-ion batteries.

Unfortunately, what we mainly do in Australia is dig for the raw materials and ship them overseas for refining, cell production and battery assembly. The fact that we are not involved in downstream processing in the battery supply chain brings us no

JAVIER ZAYAS PHOTOGRAPHY / GETTY IMAGES



Monash University's lithium-sulphur battery prototype (right), developed by the author (above right), maintains 99% efficiency for over 200 charging cycles. But its processed lithium is imported, while Australia is a major raw producer.

MONASH UNIVERSITY X2

more than 0.5% of the ultimate value of our exported minerals – a shockingly small profit.

Hopefully that will change for the better! That's become a focus for me, to advocate for a local battery supply chain in Australia or, at the very least, moving further along the battery supply chain to refining and electrochemical production stages. Such a move, although ambitious, makes far better sense than simply shipping these valuable raw materials overseas.

Historically, Australia has been a country that has done no more than mining for raw materials rather than processing them to make valuable goods and holding a prominent role in the global supply chain of various technologies. But things are about to change, because of the trade war between China and the rest of the world.

China currently controls the supply chain of batteries because they dominate the processing of the critical battery minerals. Other industrial countries, such as South Korea, Japan, USA and some in Europe, make batteries, but they rely heavily on China for those materials. If Australia could pick up that refining and processing, we would be the more reliable trading partner.

That's the "next big thing" – and that's why I am actively advocating for Australia's battery industry to become a dominant player in producing refined battery materials. Such a move is not going to happen overnight. It requires detailed and transparent roadmaps and large investments. And at the same time, it needs consistent dialogues between the government, industries, the education sector and the research sector to ensure maximum efficiency and continuous innovation.

That's why I've decided to basically get out of the lab and try to communicate the importance of moving towards a local battery supply chain. And I'm trying to communicate not only to the policy makers and industry, but also to the general public.

> "Sometimes I feel that here in Australia we are not paying attention to a world that is changing before our eyes, especially in engineering sectors."

It's very important to me that everyone understands what an opportunity this is for our country. It's not only about creating more wealth for Australia, it's also about creating a new job market and fostering national pride, while we lower our emissions and minimise the impact of climate change. If we could secure a significant foothold in the global energy market, it means that we will be greatly involved in energy storage work, and that means significant growth in the engineering job market, in line with the increasing demand for energy in national growth.

But sometimes I feel that here in Australia we are not paying attention to a world that is changing before our eyes, especially in engineering sectors. We're not good at observing and monitoring these changes so that we can adapt to them. The whole world has been moving towards the electrification of transport, for example, but we still have resistance from some policy makers here.

It's so important that the general public knows about these changes, because at the end of the day it's the general public that has the say. If the nation wants to reach net zero targets sooner than the government's plan – which is 2050, not a particularly ambitious target – you've got to inform them about the opportunities. ◉

DR MAHDOKHT SHAIBANI has a PhD in mechanical engineering from Monash University, and is a research fellow at the Monash Energy Institute.

DEEP DOWN AND DARK: STAWELL'S GENIUS LAIR

Country Victoria is set to host one of the coolest experiments going, an attempt to solve the mystery of dark matter. Will they succeed? And what's the Italian connection? **JACINTA BOWLER** dived underground to find out.

DOTTEDHIPPO / GETTY IMAGES

A small town in regional Victoria called Stawell will soon have a secret deep below its main street. One thousand metres underground in a dusty, dark gold mine will sit a brand-new, dust-free, laboratory with a dark matter detector at its core.

If you're a physicist who needs to head down there for work, the trip isn't easy. For openers you'll need to don 10kg of protective mining equipment and drive in a specialised ute down a tunnel for 45 minutes in the dark on the bumpiest road imaginable. Then you'll have to strip and shower off all the dirt and grime acquired on the way. Finally, after changing into a fresh, low-dust jumpsuit, you're ready to enter the Stawell Underground Physics Laboratory (SUPL).

"I was overwhelmed when I went down that tunnel," says Professor Alan Duffy, Swinburne University of Technology astrophysicist and former lead scientist of the Royal Institution of Australia. "It was a 45-minute journey to see this huge facility. The roof was over 12 metres high. It's such a larger space than I imagined, but clearly so full of promise."

At this depth, the smell is completely foreign. Breathable air is pumped throughout the facility, but by the time it reaches a kilometre below the surface it's hot and humid and rank. To Wayne Chapman, one of the managers of the SUPL building project, it's the smell of decades of "miners, sweat, kebabs, beer and blast fumes".

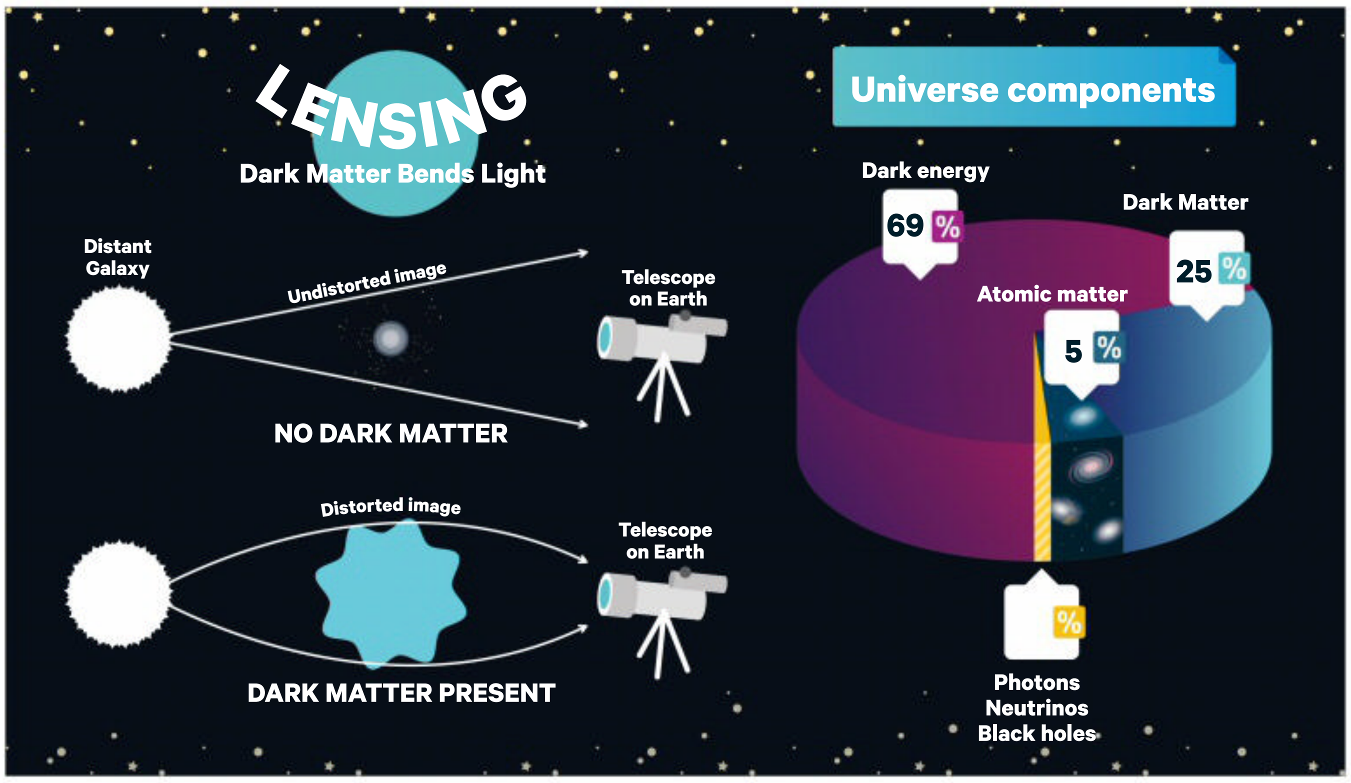
Right now, the lab – a cavernous area on a mostly unused section of the mine – is just a construction site. But if all goes to plan, by the end of 2022 a team of researchers from the University of Melbourne, ANSTO, Swinburne, and more will be collecting data, and hopefully helping to answer one of the most befuddling questions in astrophysics: what is dark matter made from?

STAWELL AND SABRE

For a town of just 6,000 that's so entwined with its gold mine, it's not surprising that when plans began rumbling back in 2014 about the first underground lab in the Southern Hemisphere being built beneath Stawell, the locals had to be convinced of the appeal.

Stawell has similarities with many regional towns of its size across Australia. It's got one high school, two post offices and a nearby national park – the Grampians. Its biggest attraction is the Stawell Gift, the oldest short-distance footrace in the country, and famously the one with the richest prize purse. If you visit outside of the Gift carnival, the locals might suggest you visit the Diamond House; the distinctive, diamond-patterned restaurant is one of the oldest houses in Stawell, having stood there since 1868.

But unlike many gold rush towns, Stawell's gold has had a resurgence. Mining in the town dates back to the 1850s, and although the gold had seemingly run out by the 1920s, in the 1980s full-scale mining recommenced, and more than 2.3 million ounces of the precious metal has since been extracted. The mine, just a few minutes' drive from the centre of town, still employs more than 300 people.



Eight years after SUPL was first announced, there's much better understanding about the experiment – thanks to the then mayor, Murray Emerson, enthusiastic science teachers at the local schools, and outreach programs run by SUPL scientists.

In particular, it's now known that the reason the detector – called the Sodium Iodide with Active Background Rejection Experiment (SABRE) – had to be so far underground was not to keep the experiment *in*, but to keep the rest of the world's radiation out.

"We're pushing the boundaries for what you can do for a scientific instrument, as well as a new type of scientific lab in Australia," says Phillip Urquijo, a technical coordinator of SABRE and University of Melbourne associate professor of particle physics. "It turns out that there is sufficient expertise in Australia to pull this together. It's been impressive."

But with years-long delays of the project due to the mine closing and then reopening when its ownership changed, plus the months of COVID lockdowns in Victoria during the pandemic, SUPL is years behind schedule and only now coming to fruition.

The tennis-court-sized cavern must still undergo some significant changes. The rock needs to be covered in a flexible coating, and rooms will be constructed and painted. Showers need to be installed, along with airconditioners to keep out the dust and humidity from the rest of the mine. Once construction is completed, the equipment for the experiment will be painstakingly transported down through the bumpy tunnels.

A COOL BIT OF KIT

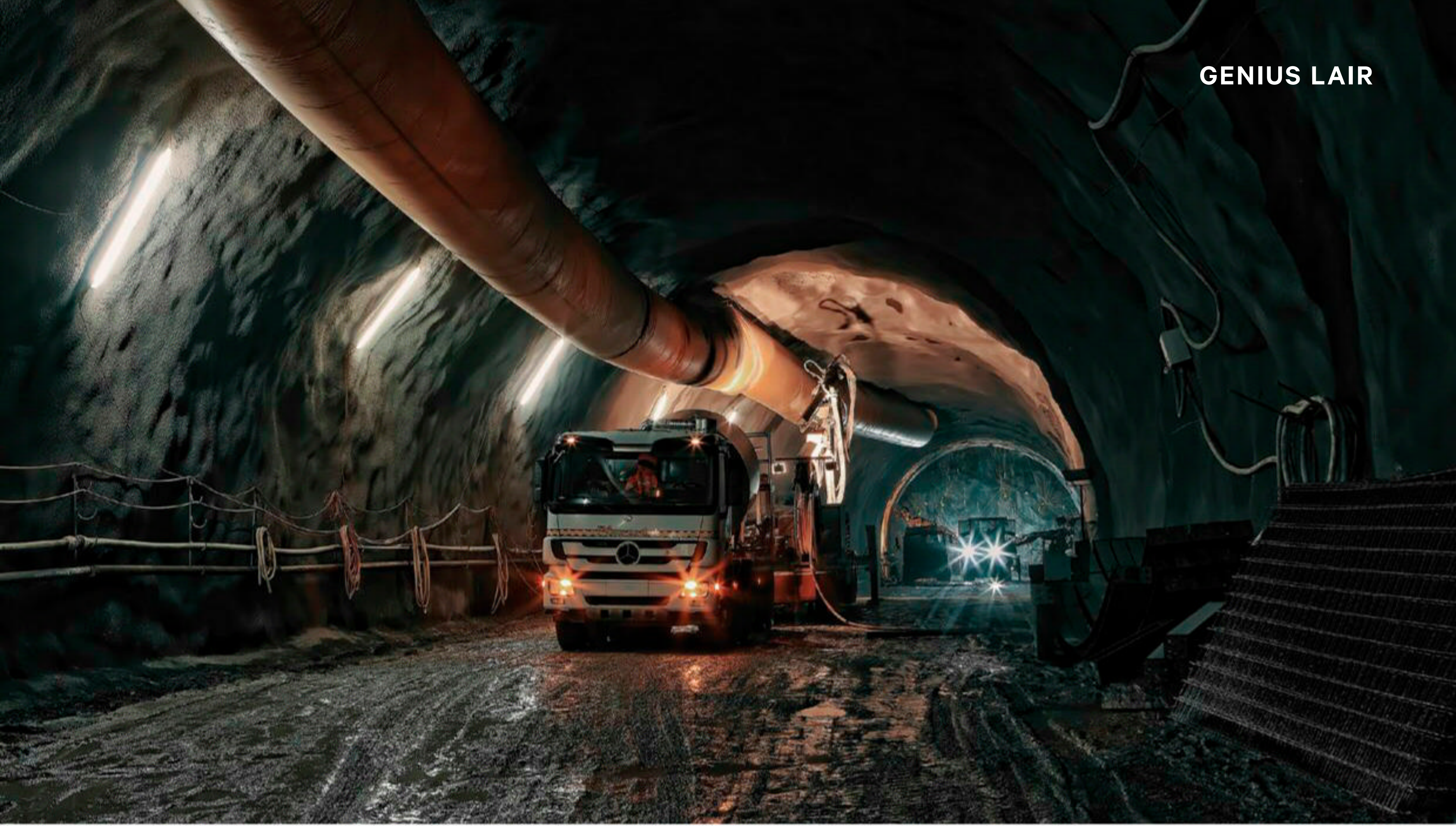
In place, the multi-million-dollar detector will look from the outside like a four-metre square box of steel. This steel casing – and its placement deep beneath the Earth's surface – is to repel as much stray radiation as possible. Housed inside is a vat called the veto vessel, which will be covered with reflector foil and filled with a compound called linear alkylbenzene. Studded throughout the inner walls of the vat are photon sensors called photomultiplier tubes that look like vintage yellow light bulbs.

Rocky renovations: Turning a mine into a lab's a multi-year process, coating rocks and finding ways to minimise dust and humidity.

SUPL

Descending from the vat's lid are long copper cylinders filled with 50kg of incredibly pure sodium iodide crystal. This is the critical part – although what it does won't happen often. When a dark matter particle travels through the crystal, it will interact with an atom inside of it; the atom will recoil and the crystal will produce a flash of light, which the detectors will be able to pick up.

The crystals need to be as heavy – and therefore as big – as possible to detect as many potential dark matter particles as they can. Think of a hand swatting a fly – the bigger the hand, the more swatting ability. In the same way, the bigger the crystal, the more likely that a weakly interacting massive particle (WIMP) will pass through and alert the detector. They also



SUPL

WHEN A DARK MATTER PARTICLE TRAVELS THROUGH THE CRYSTAL, IT WILL INTERACT WITH AN ATOM INSIDE ... AND THE CRYSTAL WILL PRODUCE A FLASH OF LIGHT

need to be as "pure" as possible to prevent radiation from interfering with accurate readings. Extending the hand analogy, impurities act like phantom flies, alerting the detector with false readings. Creating each of these individual parts has taken years of study. For example, the crystals have been developed by an international team and will have the lowest level of radioactivity ever created – a state the researchers call "radiopure".

Zuzana Slavkovska, one of the researchers testing these crystals at the Australian National University, has been using a particle accelerator to measure the crystals' purity.

"We are trying to identify and quantify these radio impurities – meaning isotopes that are radioactive – as they might produce signals that mimic dark matter," says Slavkovska. "We want to make sure when we detect something, it really is dark matter."

This is also the reason why the lab needs to be dust-free. Radiation is all around us, all the time. Ionising radiation emits from bananas (because of the potassium) for example, and from modern steel (because the production uses atmospheric air). Each piece of material that makes up SUPL has been checked for minute levels of radioactivity at specialised labs to minimise any chance of the detector picking it up. Even the talcum-powder-like mine dust would introduce small amounts of radiation, so it has to be kept out.

Each piece of the experiment needs to be transported into the mine's depth's, taking exceptional care not to damage the fragile equipment. Then the detector will be assembled piece by piece inside the mine. First the veto vessel will need to be installed, with enough reinforcements to make sure it can eventually hold thousands of litres of liquid inside. The photomultiplier tubes will be screwed into the walls. Then the team needs to coat the entire inside of the container in reflector foil.

The foil needs to cover all sides and it can't be touched. Urquijo suggests that the installation of the final bottom piece might have to be "Mission Impossible" style.

"We'll try to figure out something that doesn't involve dangling from the ceiling," he says. "But maybe we'll have to."

THE MATTER AT HAND

Dark matter hasn't been an easy thing to get our hands (or in this case, detectors) on. We've been seeing the evidence of whatever dark matter is since the turn of the 20th century, when scientists discovered that the mass and rotation of galaxies just don't make sense without an added unseen gravitational force.

By the 1980s, scientists were sure that dark matter existed, but since then they've struggled to agree on what it is or how best to detect it. It could be a brand-new type of particle, a boson, or even a primordial black hole. Each potential candidate requires its own expensive experimental set-up in order to test for its existence.

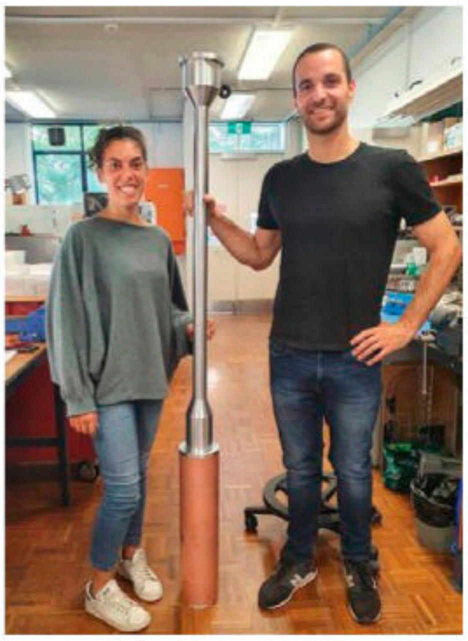
One of physicists' favourite candidates over the past few years is a hypothetical particle class called weakly interacting massive particles, or WIMPs. Scientists don't yet have a great definition for what a WIMP would be, but if it exists, it'll neither absorb nor emit light. Although WIMPs don't often interact with other particles, researchers are hoping that they'll occasionally smack into the atoms inside detectors.

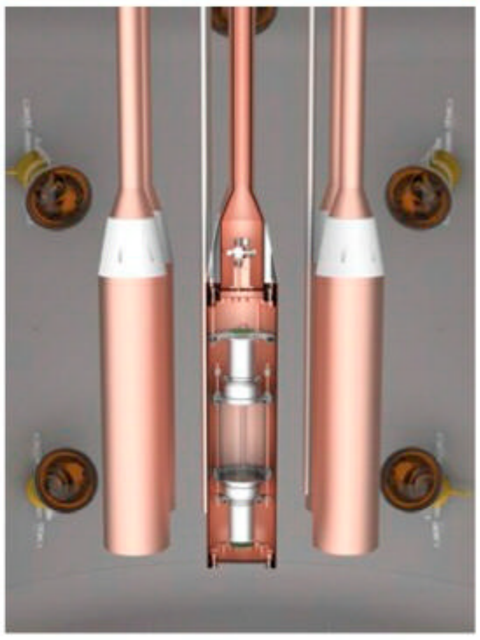
Despite WIMPs being one of our best bets for dark matter, detector after detector has been unable to find anything that even remotely resembles a WIMP. Well, all detectors but one.

The DAMA/LIBRA experiment, set up in a large underground lab underneath the mountain Gran Sasso in Italy, has been recording a significant signal for 20 years now. DAMA/LIBRA is a controversial experiment at best – while other large experiments that are far more sensitive and specific have found nothing, DAMA/LIBRA took a simpler route: it charts the data for change over time.

Radiation doesn't just exist in this dark matter. Even thousands of metres under rock where the detector lives, other kinds of radiation – such as muons from the Sun's cosmic rays or neutrons from radioactive decay – can travel.

SABRE, and many other detectors, have ways to minimise these unwanted particles. Muons, for example, can travel through the Earth from one side to the other, but they produce ionising energy, which the team can easily detect and remove from its data. Neutrons are likely to be stopped by the 12,000 litres of linear alkylbenzene inside the vat.





"THE EXCITEMENT AND POTENTIAL VALUE TO THE WORLD WOULD BE AKIN TO THE HIGGS BOSON DISCOVERY. PERHAPS EVEN GREATER."

Luckily, due to how rarely WIMPs interact with particles, they are very unlikely to hit both the crystal and the outer detector.

"We also have high-density polyethylene shielding around, and that tends to absorb neutrons as well," says Urquijo. "Plus, the neutrons will actually produce light. If we see some light occurring in the outer detector before it hits the crystal, then that tells us it's probably a neutron coming from outside."

Although scientists don't know what a dark matter signal is going to look like, one thing that we do know is that we live in a galaxy filled with dark matter.

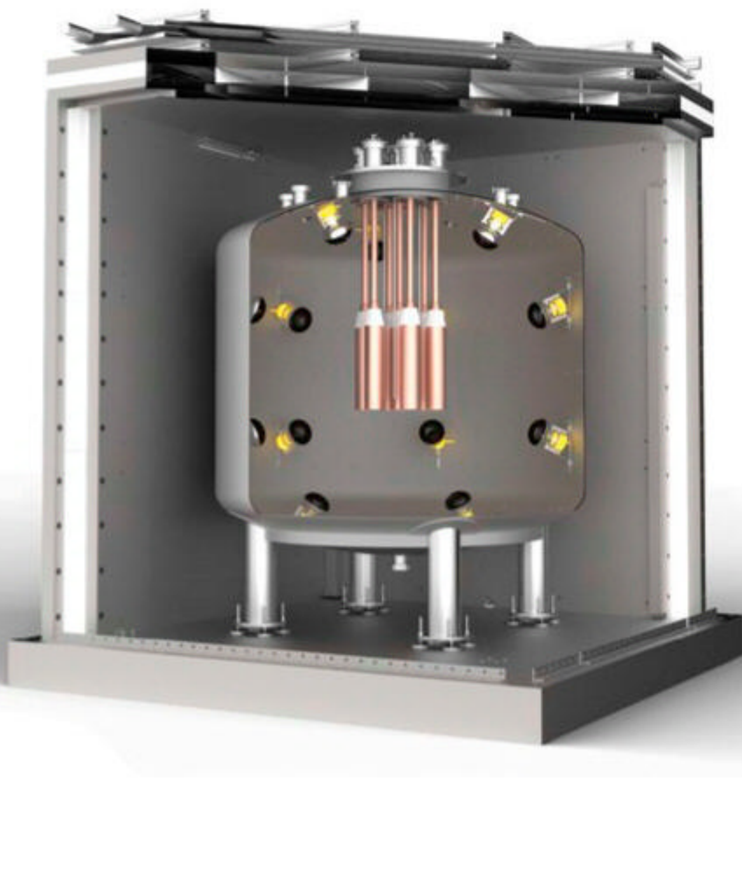
Because the Earth is physically moving through space as it travels around the Sun, researchers think that we might see a change in the amount of dark matter we see as we move, creating a signal that would repeat annually. The signal doesn't have to show the exact specifications of WIMPs or any other potential dark matter characteristics; any repeating signal that can't be explained by error or other sources *could* be dark matter. This repeating signal is known as an "annual modulation".

This is what the DAMA/LIBRA team has found: an annual modulation signal. Even more impressively, they've managed to confirm it to a high degree of confidence for almost two decades. But so far, no other detectors have been able to find this same signal. There could be a number of reasons for this.

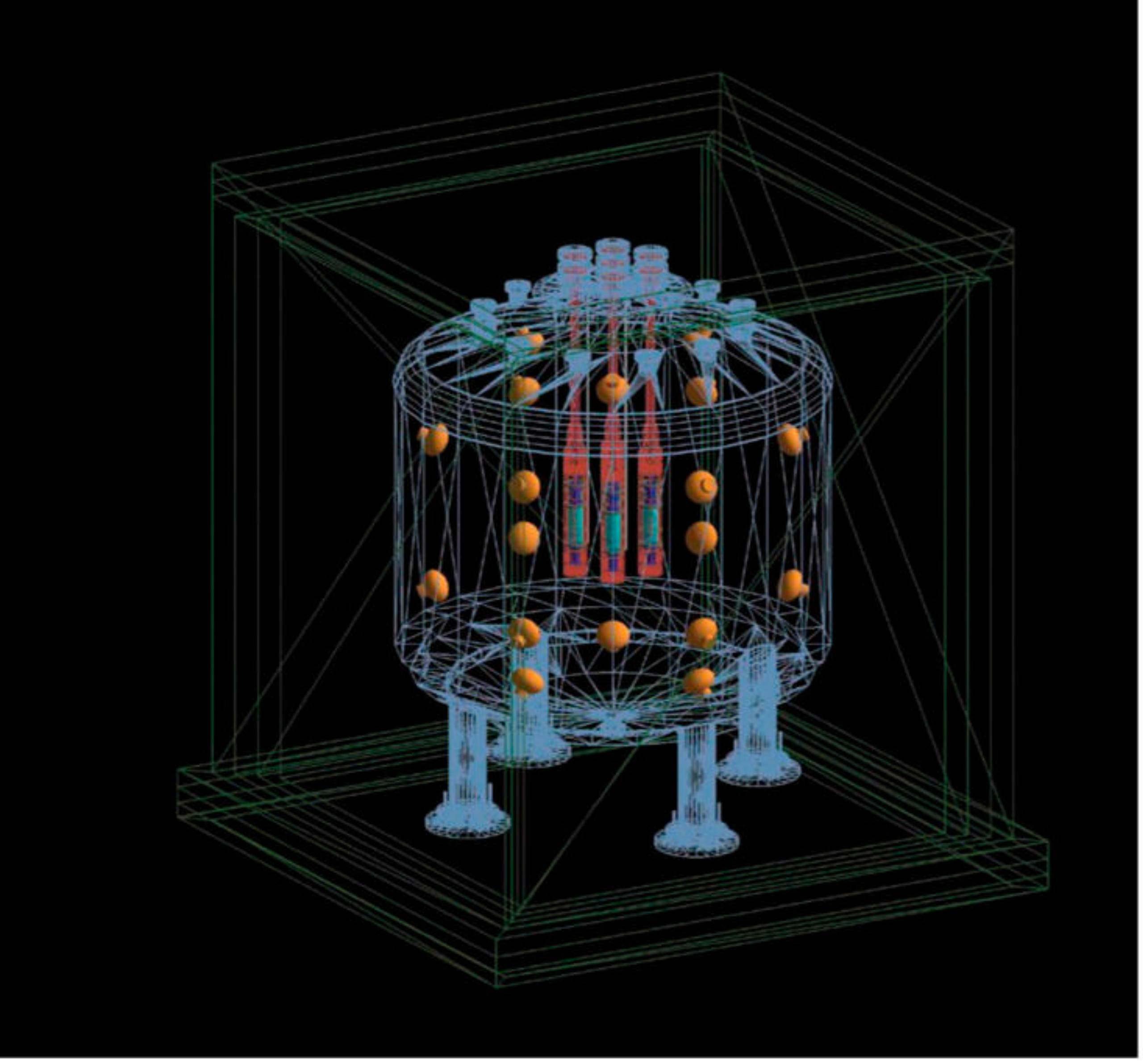
One suggestion is that instead of the annual modulation signal of the Earth moving around

THROWING LIGHT ON DARK MATTER

This diagram shows the inner workings of the SUPL. The copper-coloured crystal modules (detail above) hang near the centre of the veto vessel. The globes angled towards the centre are the sensors. The surrounding vessel is essentially its shield – sandwiched layers of steel and polyethylene.



SUPL



SUPL

Working out the exact layout of the SUPL required a complex set of simulations to model the interactions. The placement of the globes, above in yellow, and the number and size of the crystal modules had many iterations. Opposite, a cross section of the copper modules shows the crystal's position, with a prototype held by engineers Giulia Milana and Tiziano Baroncelli, at ANU.

the Sun, it is instead a seasonal change caused by something else entirely. This makes having a dark matter detector on the other side of the world incredibly handy. If the SABRE team finds modulation opposite to DAMA/LIBRA, it means that what the Italian team is seeing is seasonal variation – and it isn't dark matter. However, if the modulations match, it would confirm that we're able to detect dark matter.

But the SABRE team might also find no modulation at all. In the last few years, some physicists have suggested that the way that DAMA/LIBRA collects its results introduces a bias that could cause this modulation. An experiment called ANAIS in an old railway tunnel in Spain recently concluded that they could not find evidence of this annual modulation, despite adopting the same target and technique of DAMA/LIBRA. This result was described by some as the nail in the coffin of DAMA/LIBRA's modulation.

Urquijo strongly disagrees with that assessment, suggesting it was a form of scientific "clickbait".

"The ANAIS collaboration didn't jump to a conclusion themselves. They didn't say 'we've ruled out DAMA/LIBRA'," he says. "If you look at the difference between the two, it wasn't that much... It was not to a level that you would say it ruled out [the DAMA/LIBRA] measurement."

THE ITALIAN JOB

Clearly, SABRE is closely connected to the DAMA/LIBRA experiment. In fact, the SABRE being built in Stawell is only one of two related experiments: a second one is slated to be built in the same Gran Sasso laboratory as DAMA/LIBRA. The two projects are called SABRE North and SABRE South. They'll be identical, each one looking for an annual modulation on their own side of the world to confirm DAMA/LIBRA's result. Without the Italian project wanting to probe the hypothesis of seasonal variation, the Stawell laboratory would probably not exist.

"At the beginning, it was very important to push to have this counterpart in the Southern Hemisphere, but at this point we have progressed so much that now we are actually at the same level," says Claudia Tomei, a particle physicist at Italy's National Institute for Nuclear Physics (INFN) and one of the lead researchers on the SABRE North project. "Both projects will be able to obtain an important result – but not as important as the combination of the two."

Tomei is one of the many scientists from around the world who visited Stawell to inspect the mine and its location long before the experiments begin.

"I went there with colleagues who were interested in the project," she says. "I also got the chance to meet the community of physicists there. We are used to collaborating with scientists from abroad, of course, but Australia is so far away I have never been involved there before."

Australians, in turn, headed north to learn from DAMA/LIBRA. Even Emerson, the enthusiastic Stawell mayor when the project was first announced, travelled to Gran Sasso to see the DAMA/LIBRA detector. The collaboration is so wide-reaching that the universities of Rome, Milan and Princeton, as well as INFN, are all involved.

"This collaboration was at the beginning very strong," says Tomei. Of course, it isn't easy to collaborate on three different continents. "But we will be more connected as more of the projects enter the active stage," she says.

Although it's taken a while to get the Stawell lab off (well, under) the ground, and international trips are no longer viable to foster those connections, many people around the world – including those working at DAMA/LIBRA – are holding their breath to see what the SABRE team discovers.

Even when all the parts are in, assembled and the detector is turned on, it'll be at least three years until we can know what they're going to find. SABRE will just have to sit there waiting for the occasional mystery particles to come whizzing by. If we're lucky, some of them could be dark matter.

"What I *think* we'll see is a result that rules out DAMA/LIBRA," says Duffy.

"What I *hope* we find is a result that rules *in* DAMA/LIBRA as a discoverer of dark matter, because the excitement and the potential value to the world would be akin to the Higgs boson discovery. Perhaps even greater."

JACINTA BOWLER is based in Melbourne. Her previous story – about the science of soap – appeared in issue 91.

It *is* a laughing matter

Laughter's seen as one of those things that makes us human, but behavioural scientists are identifying species around the world who share the habit of hilarity. **JAMIE SEIDEL** finds out why it's important from an evolutionary standpoint and its implications for the field of biology.

You're a rat. In a lab. With people in odd white coats walking around you. It's not funny! Or is it?

"Having a sense of humour would certainly help rehabilitate a heap of lab rats," laughs PhD student of biological anthropology Sasha Winkler. "Rats are great. They have a rat laugh. If you tickle them, they make these high-pitched ultrasonic sounds."

Not everything about Mother Nature is fight or flight. It turns out that many of our animal cousins find time for a chortle.

Take a walk in any urban park on a summer's evening. You'll almost certainly hear children giggling and screaming as they romp together.

But what's that sound coming from the magpies cavorting under the sprinkler, or the funny noise being made by dogs gambolling over a ball? Could it be a chuckle? A guffaw? Or are we just superimposing our own expectations over what we observe?

"I think there's enough evidence that we're seeing other animals demonstrate social bonding signals, and they're reflecting positive emotional signals," says University of Melbourne animal welfare researcher Dr Mia Cobb.

"That sounds very scientific of me to describe it that way. But I don't think it's a stretch to call it laughing."

A review of a multitude of animal behaviour studies from around the world by researchers at the University of California (UCLA), in the US, suggests that the natural world is full of laughter, identifying 65 different species as laughing candidates. There's probably many more. We just don't yet know what to listen for.

The best place to start is social play, says the study co-author, Sasha Winkler. At least, that's where we're most likely to confirm a cackle.

"Your pets probably *aren't* laughing at you. *Probably*," she says. "In humans, laughing *at* someone is a sort of passive-aggressive teasing behaviour. Finding ways to identify that in animals isn't so easy." But the concept of play, evident in many species, is something we can definitely relate to.

SENSORSPOT / GETTY IMAGES

The meaning of mirth

“We’re not that special,” says Cobb. “Humans are just animals as well. So it makes a lot of sense that other highly social mammals will share a lot of the same feelings and behaviours.”

Great apes may have inherited a tendency to titter from the same ancestral source as us. They have a “play face” that looks like a smile.

Dogs may have picked up disarming humour from living beside humans for millennia. But the need to avoid misinterpreting play as pack politics has been around much longer than that.

“Dogs, when they’re play-bowing, are signalling ‘this isn’t serious … I might grab your neck – but I’m not trying to rip out your throat’,” says Cobb.

It’s a message reaffirmed by deliberate vocalisation.

“Dogs have a play growl that’s acoustically different to the growl they make when they’re aggressive,” Winkler says. “They also have a play-specific bark. So they have multiple ways to signal they want to start or continue to play.”

But is it really a laugh?

Anthropomorphism – the tendency to apply human traits to animals – is a risk.

“Dogs may be their own special case,” Winkler explains. “They’ve co-evolved with humans for so long that a lot of their facial features have been selected for how expressive they are. Their eyebrows, for example.”

> “Dogs have a play growl that’s acoustically different to the growl they make when they’re aggressive.”

But that’s where an animal behaviouralist’s comfort zone ends.

“For example, we’ve falsely attributed a guilty look to dogs,” says Cobb.

“It’s really an anticipation of our behaviour toward them. It’s appeasement. They can tell you’re about to get grumpy. Not necessarily why.”

We tend to make many such mistakes.

“The risk of anthropomorphising gets greater when it’s a distant species,” Winkler adds. “When cats make their playful purr, is that the same thing as laughter? I’m not sure.”

But she wants to know.

On a wing and a prayer

The UCLA study scoured dozens of research papers addressing animal play. Most examined physical behaviour. But among the notes and observations were buried references to unique sounds.

Some seemed obvious. Others less so.

“It was a Canadian researcher named Sergio Pellis who told us, ‘Hey, you’re missing how magpies have a call that they make during play’,” says Winkler.

The US study only found three birds showing such signs of joyous vocalisation – and all are antipodean: the Australian magpie, the budgerigar and New Zealand’s kea.

But do birds really want to have fun?

“A lot of scientists don’t think birds can play. But I do,” Winkler states. “You can watch a bird like a kea repeatedly rolling down a bank of snow with no obvious benefit beyond fun. They do it repeatedly. And they seem to be enjoying themselves.”

Cobb agrees. “You’ve got a highly sociable animal in the magpie, that we know lives in intergenerational groups. It sounds to me like it would make a lot of sense for them to have ways to bond and show those affiliative relationships among each other.”

The kea is a particular case in point. It has a specific call associated with fun. And when other keas hear that call over a speaker system, they spontaneously begin to frolic.

“They’re cheeky birds,” says Winkler. “Just hearing a kea’s warbling call makes others feel playful or puts them in a positive mood. It’s such a cool study. Not all animals have a response where the cause is so clearly tied to a playful vocalisation.”

Why magpies? Why keas?

“The common factor is how social they are.”

Parakeets also show signs of play. But are those cocky crows laughing at your misfortune?

“I wouldn’t mess with the corvids,” warns Cobb.

Just among friends

Despite the ubiquity of play in the animal kingdom, the evolutionary benefits aren’t clear.

“The ancient aspect of laughter, in its purest form, is what human babies give us,” says Cobb. “Even children who are born blind and deaf will laugh. So there’s certainly something innate about it.”

But it burns energy without immediate benefit. It distracts the participants. It attracts attention. Such a risk-reward equation doesn’t seem to add up.

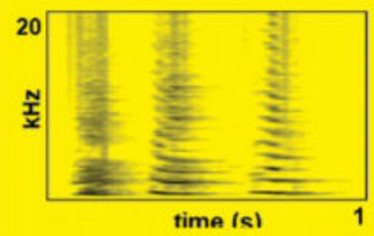
“We argue in our paper that playful vocalisations – laughter – are likely to be quiet,” explains Winkler. “Most animals just want to signal to the willing partner they’re playing with. They don’t want attention from predators or others of their species.”

That appears to be the default condition. But then there are keas. And elephants. And humans. They laugh out loud.

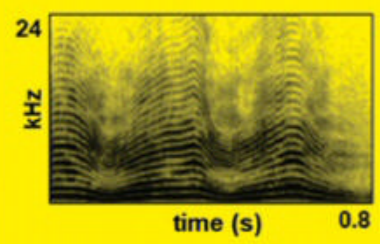
“In these cases, we think there’s a group function for laughter. When you’re laughing with a friend,

HUMAN

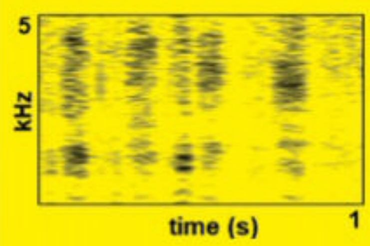
DOMESTIC DOG



KEA PARROT

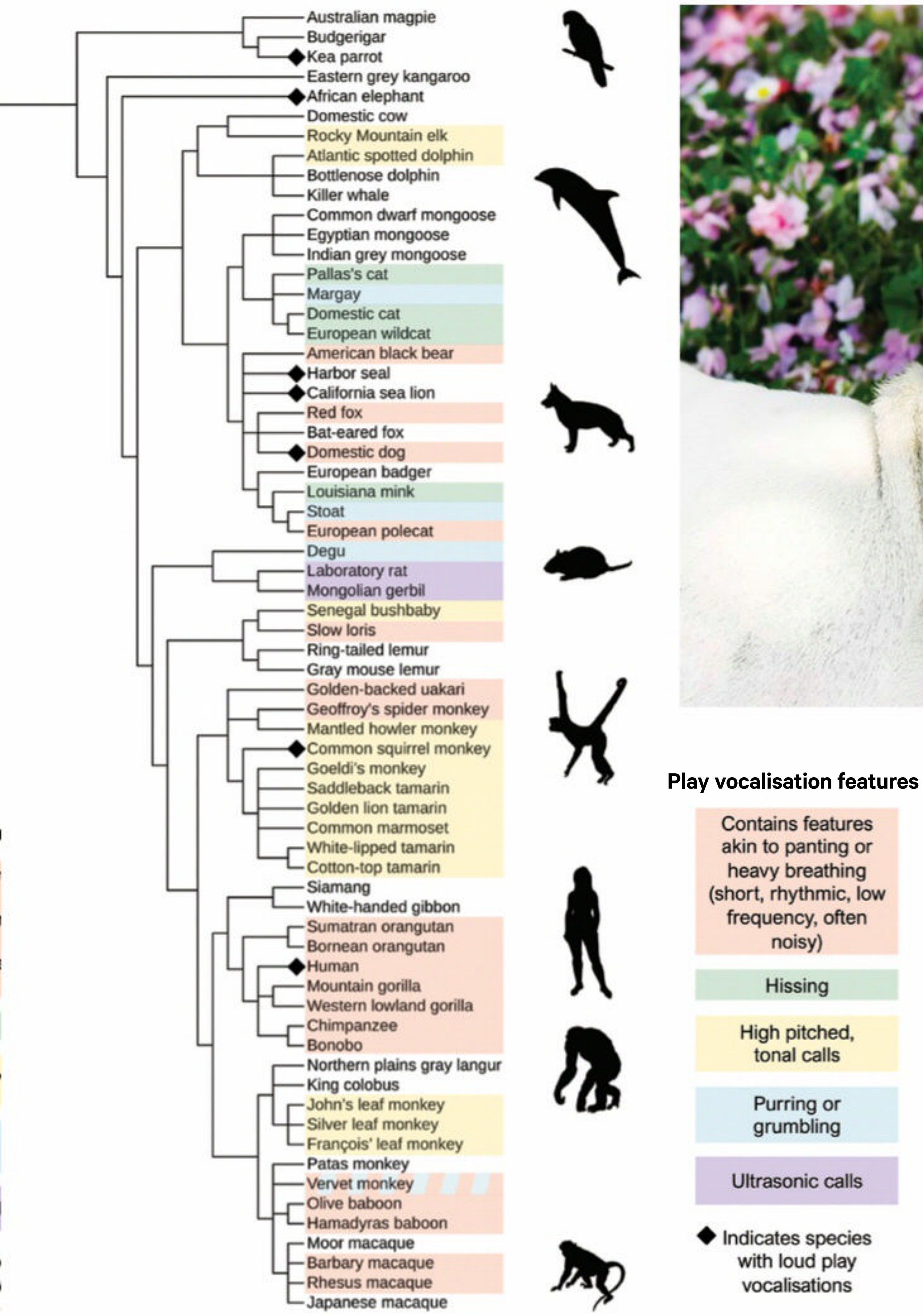


CHIMPANZEE

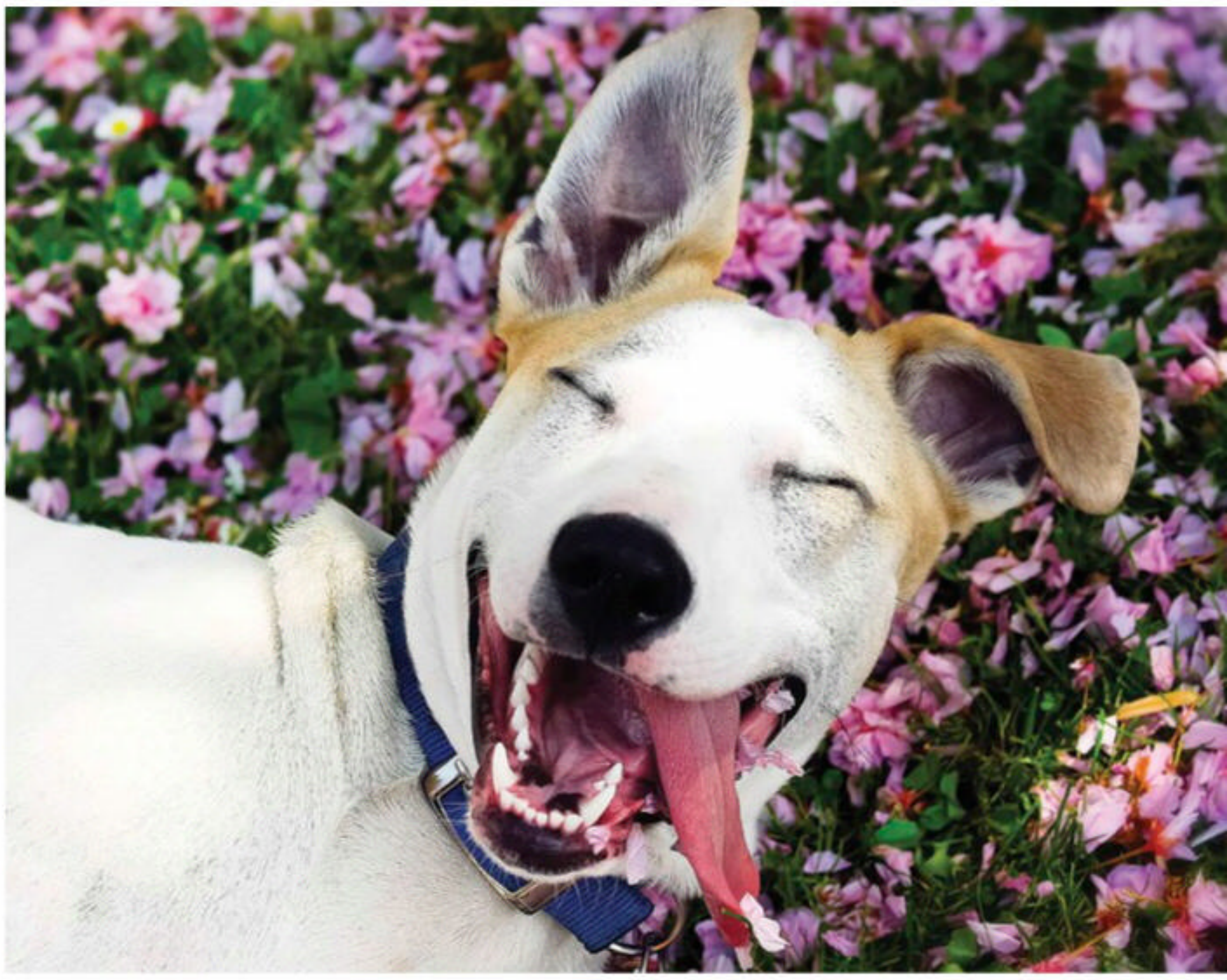


A recent study recorded the play vocalisations of 65 species that may be capable of laughter, as shown on the spectrograms above and over the page. The diagram (opposite) illustrates the phylogenetic relationship between these species, as well as the types of vocal features observed. But the question remains whether the vocalisations – like those of orangutans, kea, dogs and budgerigars – are genuine expressions of mirth, or wishful projections by us humans.

SPECTROGRAPHS: WINKLER AND BRYANT



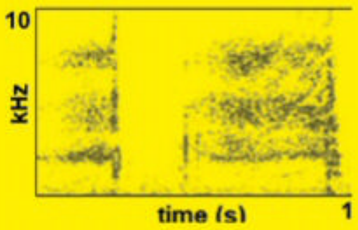
Australian magpie
Budgerigar
Kea parrot
Eastern grey kangaroo
African elephant
Domestic cow
Rocky Mountain elk
Atlantic spotted dolphin
Bottlenose dolphin
Killer whale
Common dwarf mongoose
Egyptian mongoose
Indian grey mongoose
Pallas's cat
Margay
Domestic cat
European wildcat
American black bear
Harbor seal
California sea lion
Red fox
Bat-eared fox
Domestic dog
European badger
Louisiana mink
Stoat
European polecat
Degu
Laboratory rat
Mongolian gerbil
Senegal bushbaby
Slow loris
Ring-tailed lemur
Gray mouse lemur
Golden-backed uakari
Geoffroy's spider monkey
Mantled howler monkey
Common squirrel monkey
Goeldi's monkey
Saddleback tamarin
Golden lion tamarin
Common marmoset
White-lipped tamarin
Cotton-top tamarin
Siamang
White-handed gibbon
Sumatran orangutan
Bornean orangutan
Human
Mountain gorilla
Western lowland gorilla
Chimpanzee
Bonobo
Northern plains gray langur
King colobus
John's leaf monkey
Silver leaf monkey
François' leaf monkey
Patas monkey
Vervet monkey
Olive baboon
Hamadryas baboon
Moor macaque
Barbary macaque
Rhesus macaque
Japanese macaque
Play vocalisation features
Contains features akin to panting or heavy breathing (short, rhythmic, low frequency, often noisy)
Hissing
High pitched, tonal calls
Purring or grumbling
Ultrasonic calls
◆ Indicates species with loud play vocalisations





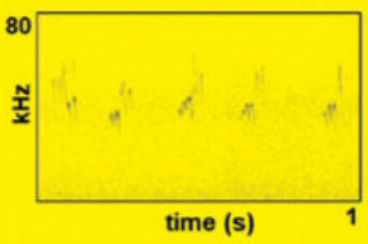


GOLDEN-BACKED UAKARI

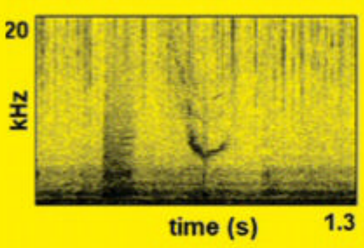


BARBARY MACAQUE

LAB RAT



BOTTLENOSE DOLPHIN



Red-tailed black cockatoos, sheep, elephants, chimpanzees and magpies are all social creatures, and all give impressions of playful vocalisations – from quiet hissing to harmonic barks, noisy chattering to ultrasonic trills. Examples of these vocalisations for other species are displayed on spectrograms above. But do animals really see the funny side of life?

CLOCKWISE FROM BOTTOM LEFT: LEA SCADDAN, FRANK ROTHE, LEA SCADDAN, PETER CADE, MANOJ SHAH / GETTY IMAGES SPECTROGRAPHS: WINKLER AND BRYANT

you're broadcasting your friendship to others," says Winkler. In humans, that signal can be complex.

"We've developed more recent uses for laughter that are complex – the derision or schadenfreude of getting some aspect of pleasure through watching others suffer or be excluded from a group," Cobb says. "It's not to say that animals don't do that. But we haven't explored that aspect yet."

In humans, the message can carry profound meaning.

"There have been studies that show we can tell if a laugh is between old friends or if they've just met," explains Winkler. "You can just imagine it, right? A sort of timid awkward laughter with someone you've just met versus a relaxed guffaw with someone you know well."

So it seems logical that such subtlety also exists in the wild.

"I think there's a lot of broadcast signalling going on in large social networks," she adds. "Laughter is an important part of our social world."

Morbid curiosity

"Wouldn't it be great if, instead of monitoring distress signals in commercial poultry sheds, we were monitoring how happy they sounded?" asks Cobb.

Animal welfare isn't just about minimising harm and suffering. It's about maximising positive emotional states.

"Laughter has fallen between the cracks," Winkler says. "Animal behaviour studies historically have focused on negative behaviours and emotions."

Tides are turning.

"There's been a distinct change since I was doing undergraduate studies in zoology 22 years ago," says Cobb. "The thought of being a canine welfare scientist wasn't really on anyone's radar back then."

Perky pigs, sniggering sheep – laughter has some hefty ethical implications.

"If you know that pigs can have a rich and meaningful social life, that means they're suffering when they're held in restriction or isolated. So what might that mean for the bacon you like eating?" asks Cobb. "That's a really uncomfortable thought for many people."

As is the motivation behind studying laughter itself.

"I do feel that the motivation behind a lot of these studies has been rooted in how it can serve us," Cobb adds. "I would love to see research that's conducted with the ultimate goal of better understanding animals and how we can help them, rather than prioritising how we can better understand or serve ourselves." After all, laughter tends to be contagious anyway. "Anything that brings groups together in a positive way is something we can all revel in."

> "Perky pigs, sniggering sheep: laughter has some hefty ethical implications."

A comedy of global proportions

There's still a possibility that magpie is howling at your feeble ground-locked existence.

Your dog may be sniggering with a friend over the way you fumbled that catch.

It's just we have no way of knowing.

And then there's our own insecure human nature.

"People have such a drive to anthropomorphise animals and to see human motives in them," says Winkler. "If you do something embarrassing, you sort of look around to see if anyone saw you. And you see a bird in a tree, looking at you, making a clear call. Of course you pin your embarrassment on that bird. But it tells you more about yourself than the bird."

Which is why it's so important to identify a laugh as a laugh. And once a candidate laugh is identified, it can be tested.

The contagious effect of kea chortles is driving similar experiments among apes.

"We're hoping to do some cognitive tests that measure their emotions, their optimistic bias," Winkler says. "Animals, like people, tend to act more optimistically when in a positive mood. We're hoping that will be one way to test for the cognitive effects of laughter."

There's little doubt real laughter exists among nature.

"It's got to a point where we see so many similarities it would be almost negligent not to say yes, animals are experiencing these feelings in a way very similar to how we humans do," says Cobb.

It's now a matter of winning widespread acceptance of this concept.

"Through advances in neuroscience, we're beginning to better understand our own thoughts and emotions," says Winkler. "We know a reward circuit exists in human brains, for example. So we can look for it in mice and other animals. As human cognitive psychology and neuroscience advance, it opens up more opportunities to also look at animals."

So, can we expect keas in MRI machines?

"Sure," Winkler chuckles. "They've already trained dogs to hold their heads still and sit in an MRI. So many interesting things have come out of that. We're starting to learn what they're thinking when they look at what their owner is doing…"

JAMIE SEIDEL is a freelance writer based in Adelaide.

What if time goes in two directions?

two directions?

T violations, timelords and the end of what we accept. Sounds crazy – but so do all scientific revolutions that change the world. **LAUREN FUGE** talks to the physicist behind a quantum theory of time, the experiment testing it right here, right now, and its implications for the future of physics – and for us.

When I was a kid, I used to lay in bed at night and try to hold the universe in my head.

Eyes tight shut, I'd let the edges of my mind rush out in all directions, imagining that it was the fabric of space expanding. The planets would rapidly recede from view; I'd soar past billions of stars until the glittering disc of the Milky Way spun before me. But I didn't stop there. I'd continue onwards and outwards until I'd thrown my mind out so far that I cradled the entire cosmos inside my skull.

Then I learnt that the universe has no edge.

That threw a spanner in the works.

There is – as 10-year-old me discovered – no boundary to the universe, no outside in which it is suspended. It just is. Suddenly, my space explorations faltered. This new knowledge didn't tessellate with anything I knew about the everyday world in which I was embedded, in which everything was embedded.

Tucked neatly into the rectangular prism of my bed, snug beneath the doona, I tried to imagine a map with no edge. I'd been holding an inky black ball in my head, watching it seethe with the shining threads of galactic superclusters, but every time I tried to delete the boundaries from that thought, my virtual cosmos became slippery. Instead I'd just slide back into the model of the universe that was comfortable – but wasn't actually real.

I couldn't force myself to make that radical shift in perspective – which is exactly how I felt when I learnt about Professor Joan Vaccaro's quantum theory of time.

Vaccaro, a quantum theorist at Griffith University in Queensland, has a theory that posits that time doesn't just move forwards in a relentless march away from the Big Bang towards chaos, but moves backwards as well – and we can't tell which timeline we're in, which technically means we're in both.

"We're in a superposition of going into the future as well as the past," Vaccaro sums it up.

Talking to her is like trying to hold an infinite universe in my head. Our conversation runs in cycles: Vaccaro explains a concept to me, I think I understand it and repeat it back to her for clarity, then she says, "No, not quite, it's more like this…" Then I attempt to understand and summarise it again, then she says, "No, not quite, it's more like this…"

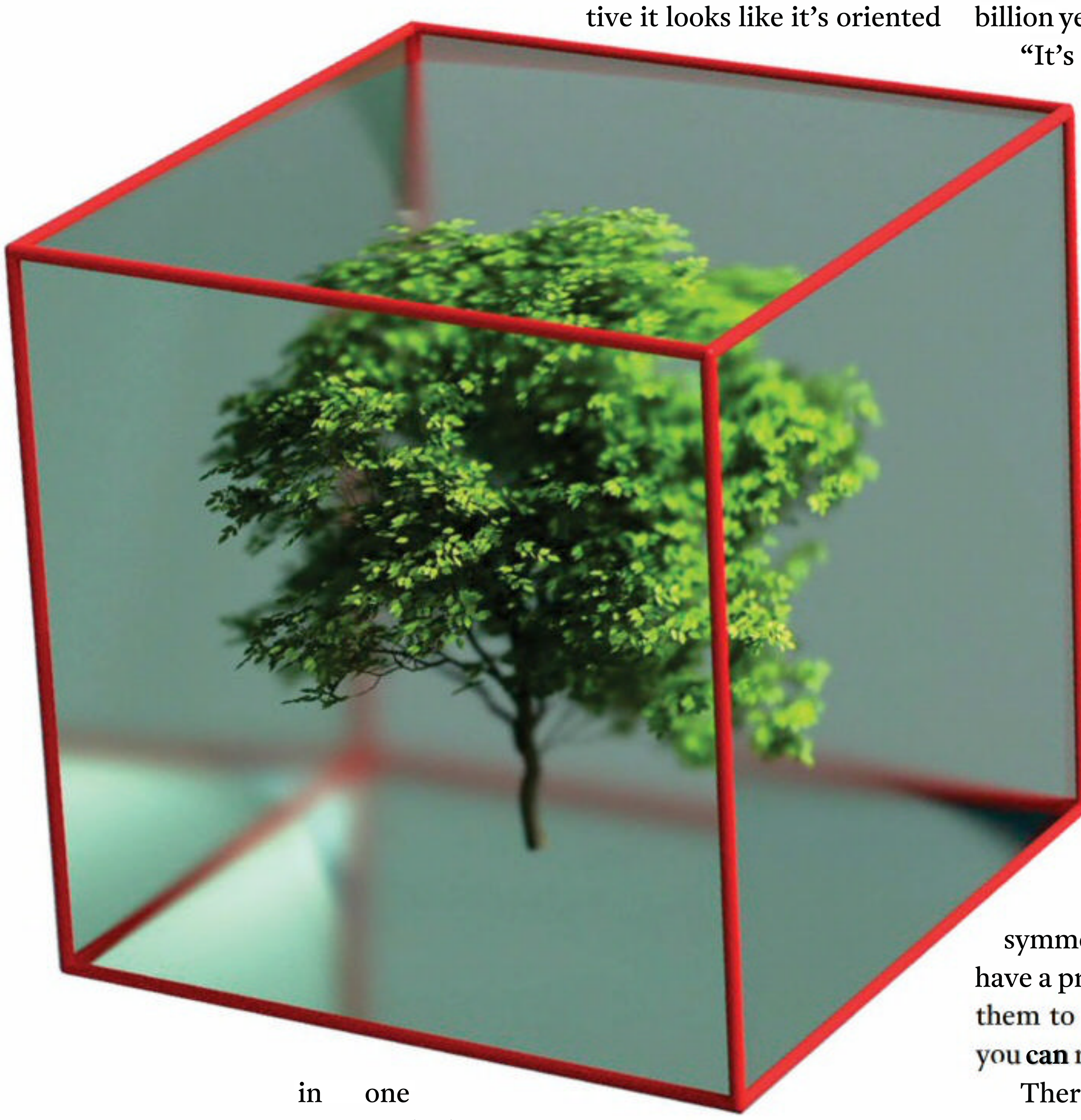
LNM / GETTY IMAGES

I just can't see the shape of it in my head, can't shift my brain to encompass a universe in a superposition of past and future. Time is one of the things that's just *true*. The sky is blue, water is wet, and time moves forward – never backwards, and certainly not both ways at once.

I confess to Vaccaro that I feel limited by my own perspective – and she tells me that she, of course, had initially felt the very same way.

Vaccaro asks if I've heard of the Gestalt shift. I start to sift through a mental tangle of particle physics to reach my memory, but she's already explaining that it's the experience of seeing something one way, and then suddenly snapping to another.

"The most famous example is a three-dimensional box, drawn just with the edges. From one perspective it looks like it's oriented in one way, and then somehow, that can shift from a different perspective. It's like that – you have to force your imagination to see it from another perspective."



I remember, then, the optical illusion made famous by Austrian philosopher Ludwig Wittgenstein where a duck becomes a rabbit, and the illustration that shows both a young and old woman. At first you only see one image – but squint, or refocus your vision, and suddenly you can't believe you ever thought there was only one way of understanding it.

The quantum world is filled with counter-intuitive ideas that stretch our minds beyond comfort. Waves are also particles, everything is a matter of probability, particles can be entangled over light-years, the cat is both dead and alive at the same time…

And the universe is in a superposition of going into the past and the future.

That's not even the weirdest part of Vaccaro's theory.

"If we're made of matter going into the future, we're made of antimatter going into the past – the symmetry requires that," she says.

"Right now, I'm made of matter and it's 13 billion years after the Big Bang – I'm in a superposition of that state, as well as being made of antimatter and 13 billion years before the Big Bang.

"It's this strange thing: those two times are together, now."

And we don't know which one is correct, she says, because when you're made of matter, everything looks like matter, and when you're made of antimatter, everything looks like antimatter.

Confused? So are physicists.

Time is such a basic component of our lives that you'd think we would have nutted out how it works by now. But the nature of time is still a mystery, to philosophers and physicists alike. Physicists are particularly puzzled by why it flows from one direction (the past) to another (the future).

This problem is visible even in our most basic equations. Physics is built on equations of motion that tell you how things change over time. Usually, you're interested in finding out how something will change into the future – for example, the position of a ball after you throw it.

But these equations themselves are actually symmetric in time, Vaccaro explains: "They don't have a preference for either direction, so you can use them to find out what was happening in the past – you can retrodict as well as predict things."

There's a problem here. Time itself is quite different going in each direction. For example, the second law of thermodynamics tells us that entropy increases with time – that even though stars ignite and spin together into new galaxies, on the whole the universe is moving from order to disorder.

The size of the universe isn't symmetric in time either – if you're going into the future, the universe expands; if you're going into the past, it's shrinking.

"So we end up with a lot of things called 'arrows of time'," Vaccaro says. "These all point in a direction. The real mystery is to try and connect that direction

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> If the forward march of time is a shaking tree, it's the wind – T-violations – driving it, not the fluttering leaves (entropy).

with equations of motion, which don't have a particular direction."

For the last 150 years, physicists have been trying to solve this mystery using asymmetric boundary conditions – basically, picking initial conditions or constraints for an equation that are different to the final conditions, like setting the starting position of a ball in projectile motion equations, or the amount of entropy at the beginning of the universe in cosmological models.

"Then you get a direction, and it's pointing to something like bigger entropy or the universe being bigger," Vaccaro says.

But what if there's a different answer – what if, Vaccaro wonders, the equations of motion themselves are asymmetric?

That's where her theory sprang from. Following this mathematical logic has led her to propose that the fact that things change over time isn't a built-in feature of nature. Rather, it's caused by a fundamental break in time-reversal symmetry.

Imagine a tree, ruffled by the wind. While the fluttering leaves may appear to be shaking the tree, they aren't responsible for the motion – they're the result of another force, the wind. In Vaccaro's theory, entropy (the leaves) may appear to be driving time forwards, but it's actually caused by symmetry violations (the wind).

This is a major divergence from accepted physics, and she knows it.

"When you try something really novel – really really novel, when it's just something novel, it's fine – but when I started this work, I kind of had to not be a physicist," Vaccaro says. "I was throwing away very cherished things in physics in order to come up with this theory."

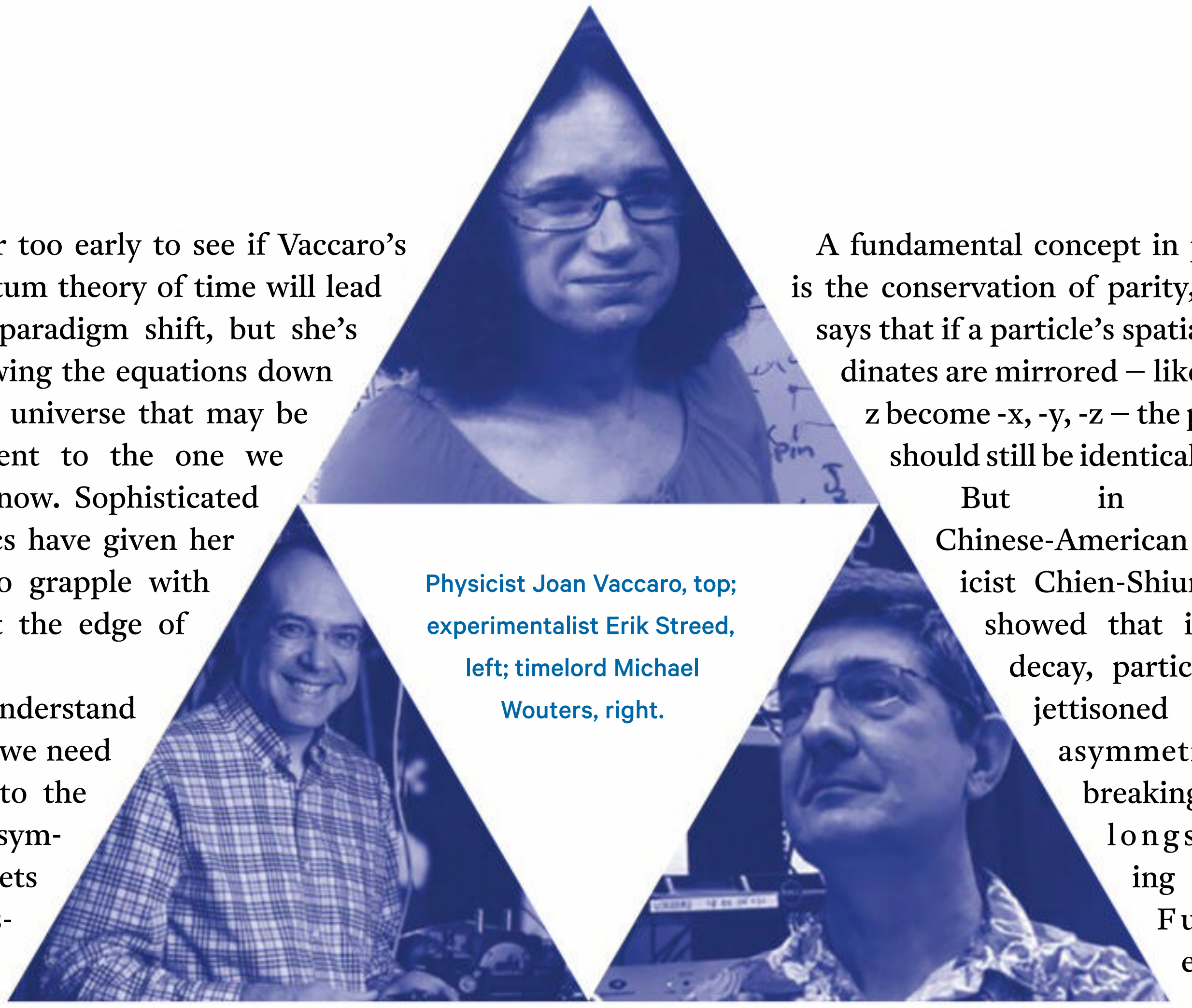
WHEN THE physicist-turned-philosopher Thomas Kuhn wrote *The Structure of Scientific Revolutions* in 1962, he sought to change how science is understood.

His book argues that science is not a relentless march of progress, forever moving onwards and upwards, but instead an alternating series of two phases: "business as normal" and "revolution". Every now and then, entire fields are plunged into turmoil by the proposal of new fundamental concepts that – if they are recognised – transform the field, catapulting it into a new "business as normal" phase.

Take, for example, the shift from the physics of Aristotle – who proposed that the natures of objects determine how they behave – to the physics of Galileo and Newton, who proposed that the behaviour of objects is governed by laws of nature.

Kuhn called such revolutions "paradigm shifts". Suddenly, scientists can no longer work within old frameworks; a period of revolution has fundamentally altered their perspective on the field. Watching a swinging pendulum, Aristotle saw an object trying to achieve its natural state, at rest on the ground, while Newton saw an object obeying the laws of gravity and energy transference.

What changes after a paradigm shift, according to Kuhn, is not just the knowledge of scientists working within a field, but the world itself. Reality can't be described separately from the conceptual schemes through which we observe it, so a scientist working under a new paradigm is a scientist studying a different world.



Physicist Joan Vaccaro, top; experimentalist Erik Streed, left; timelord Michael Wouters, right.

NATIONAL MEASUREMENT INSTITUTE, GRIFFITH UNIVERSITY X2.

It's far too early to see if Vaccaro's quantum theory of time will lead to a paradigm shift, but she's following the equations down a path to a universe that may be very different to the one we think we know. Sophisticated mathematics have given her the tools to grapple with concepts at the edge of imagining.

To understand the theory, we need to delve into the history of symmetry. It gets a bit physics-heavy, but hang in there – there are timelords at the end of it.

We see symmetry every day – just look into a mirror and wave, and your reflection will wave back at you. But symmetry also applies to many physical systems, and it basically means that these will remain unchanged even after a transformation. For example, if you move a machine from one point in space to another, it will still work as long as all the relevant environmental conditions are moved along with it. It will also still work even if you move it to any point in time. This conservation rule applies to the laws of physics, too – they remain the same wherever or whenever you are.

Physicists used to believe that symmetry governs every process in nature. It gives boundaries to the world, allowing things to act in predictable, repeatable ways and ensuring we don't live in a universe of chaos.

Some have called this the most beautiful idea in physics.

Problem is, it isn't entirely true.

Throughout the 20th century, as physicists began diving into the weird world of particles, they noticed that some weren't playing by the rules.

> "It seems like T violation is the thing which forces the universe to move, and not remain at one point in time. Without T violation, it would be a blip."

A fundamental concept in physics is the conservation of parity, which says that if a particle's spatial coordinates are mirrored – like if x, y, z become -x, -y, -z – the particle should still be identical.

But in 1956, Chinese-American physicist Chien-Shiung Wu showed that in beta decay, particles are jettisoned out asymmetrically, breaking this longstanding law. Further experiments found violations of charge-parity (CP) symmetry, which says that if a particle is changed to an antiparticle and its spatial coordinates are inverted, then the laws of physics should still be the same. In 1964, researchers at the Brookhaven National Laboratory in the US found this to be untrue for the decay of particles called kaons.

This discovery strongly implied that there must be time symmetry violation as well, since it's closely related to CP symmetry. Direct evidence was finally found in 2012 at the SLAC National Accelerator Laboratory in the US, where physicists studying the decay chains of B-mesons found that these transformations had a preferred "direction". This rule-breaking was dubbed "T violation".

"All these violations have to do with the weak force," Vaccaro explains, referring to one of the four fundamental forces of nature: strong, weak, gravity and electromagnetic. "If you look at the equations of motion for the weak force, it's time asymmetric… If time was going in the opposite direction, we would see a different evolution."

Using these ideas as a leaping-off point, Vaccaro began working on a new theory of time in 2007.

"I created a theory where we would have two types of evolution, two kinds of dynamics," she says. "Our equations at the moment only describe one, and that's the one associated with going into the future. They don't describe the other one, which we know is there from these experiments."

This, of course, is the evolution of a system going into the past.

Vaccaro explains her theory using the analogy of the double slit experiment, which you might remember (though perhaps not fondly) from high school physics.

The experiment demonstrates that light and matter can behave like both waves and particles. In the classic set-up, a laser illuminates a plate with two parallel slits cut into it. When the light passes through, it doesn't create two bands of light on the screen behind the plate, but instead creates an interference pattern of bright and dark bands – the result of a superposition of two waves.

In a fit of quantum weirdness, if you decide to observe *which* slit a single particle passes through, the interference pattern doesn't appear.

This idea has been applied to Vaccaro's model.

"The thing is, we shouldn't know which direction of time we're going in," she explains. "It's like [the universe] can't decide which slit to go through, so it has to go through both."

This is where the concept of T violation becomes critical. In her models, when T violation is "turned off", this interference disappears; when it's turned on (which reflects reality, as B-mesons tell us that T violation exists), the interference returns.

"Without T violation, according to this theory, there wouldn't be any time evolution," Vaccaro says.

"It seems like T violation is actually the thing which forces the universe to move, and not remain at one point in time. Without T violation… it would just be a blip. Imagine a galaxy coming into existence and then disappearing, existing just for a moment."

From the mathematical structure built up with these concepts, Vaccaro says all of the equations of physics emerge – the laws of motion and conservation are symptoms of T violation.

"It's a grand claim," she admits with a laugh. "And that's the remarkable thing about T violation, if you can be imaginative enough to see how the universe could use this asymmetry… in a way that gives us the properties that we understand of time, like this feeling of moving forwards in time.

"Anyway, that's the story. It's a wild one. I'm very happy with it."

But all grand claims – even quantum ones – need to be testable.

EARLY IN THE 16TH CENTURY, the Polish astronomer Nicolaus Copernicus proposed an idea that literally changed our understanding of our place in the universe.

Centuries previously, around 150 CE, Alexandrian astronomer and mathematician Claudius Ptolemy put forward a mathematical model of the cosmos that placed the Earth firmly at the centre. It assumed that the Earth is stationary at the universe's heart and that everything – from the Sun to the planets to the stars – travels in circular motions around it.

But there was a small problem. When viewed from the Earth, the planets occasionally appear to travel backwards across the sky.

To account for this retrograde motion, Ptolemy added some orbital quirks into his geocentric model, devising the idea of "epicycles" where planets complete loops within their circular orbit. With this, he found that his model could explain the observed behaviour of the planets.

For more than a thousand years, we sat snugly at the centre of the universe. But in 1543, Copernicus turned the world inside out.

He published a comprehensive new theory that positioned the Sun at the centre of the solar system and set the Earth in motion around it. With that single switch, the model could explain the rising and setting of the Sun, the movement of the stars, the cycle of the seasons and the retrograde motion of planets – with an elegant simplicity that starkly contrasted with Ptolemy's epicycles.

Copernicus still didn't have all his ducks in a row – he kept some of Ptolemy's odd orbital ideas – but the heliocentric model changed our worldview and paved the way for Galileo, Kepler, Newton, Einstein, and the field of astronomy as we know it today.

Five centuries later, a theorist, an experimentalist and a timelord walk into a nuclear facility.

The theorist says, "What if the vast streams of neutrinos produced by this reactor locally violate time reversal symmetry and fundamentally transform our understanding of the nature of time and space?"

The experimentalist says, "Nice theory, but is there anything we can measure?"

The timelord says, "I've got a clock for that."

Vaccaro's quantum theory of time proposes that T violation can be created locally by something on the quantum scale. Enter neutrinos: almost massless subatomic

"You never know, right? That little unusual-looking rock, you've got to investigate it, you've got to dig it up, see if it's connected to something else."

particles that come in three types, or "flavours": electron, tau and mu. Previous experiments looking at how the flavours change have hinted that neutrinos exhibit T violation.

"If we inverted time, the way that they changed flavour would be slightly different," Vaccaro explains. "That's the T violation – it's actually just this very subtle thing."

In places where there are tonnes of neutrinos, the theory says there may be a measurable shift in time – if you've got more T violation, you're pushed further into the future.

One mass producer of neutrinos is the Sun, but that's a bit toasty for an experimental set-up, and a long commute to boot. Luckily, nuclear reactors also churn out neutrinos and antineutrinos by the trillions, and they're marginally easier to access.

That's how the Open Pool Australian Lightwater (OPAL) reactor in Lucas Heights, Sydney, spent half of 2021 hosting the first experimental test of Vaccaro's theory. This place – Australia's only nuclear reactor, run by the Australian Nuclear Science and Technology Organisation (ANSTO) – looks like it's directly off the set of a sci-fi movie, with shining machines and pools glowing vibrant blue. The reactor is dedicated to research and is normally used to produce radioisotopes for cancer detection or neutron beams for fundamental materials research.

Vaccaro and team – including Griffith University experimental physicist Erik Streed and the National Measurement Institute's (NMI) Michael Wouters – didn't need the reactor itself. They only needed to be in the same room. In December 2020, they placed two super-precise caesium atomic clocks (plus a few back up clocks) near the reactor, one five metres away and one 10 metres away, and then left them for six months. They hoped to see the clocks run differently – and pin the blame on neutrinos.

Time dilation isn't a new idea, explains Wouters. We've known for decades that things like gravity affect how clocks tick.

"Say you've got two caesium atomic clocks and you compare them at the base of a mountain," he says by way of example. "If you take one caesium clock up a few thousand metres, leave it there for a while and then bring it down again, those clocks will not agree with each other. There'll be a discrepancy that is due to the effect of gravity on the way a clock ticks."

So perhaps, the team hypothesised, clocks could be affected by neutrinos too. They don't know whether the clocks will run faster or slower, but if they fall out of sync, it could indicate that T violations are occurring – and tell Vaccaro that she's on the right track with this theory.

And of course the experimentalist, Streed, is excited: "Nobody has put a high-precision clock next to a nuclear reactor before. It's a rock that nobody has looked under."

The OPAL reactor is the perfect place to test this part of the theory, because it's an extremely well-studied system. They know how many neutrinos it's producing when it's on and when it's off, so they can compare how the clocks are ticking along in each situation.

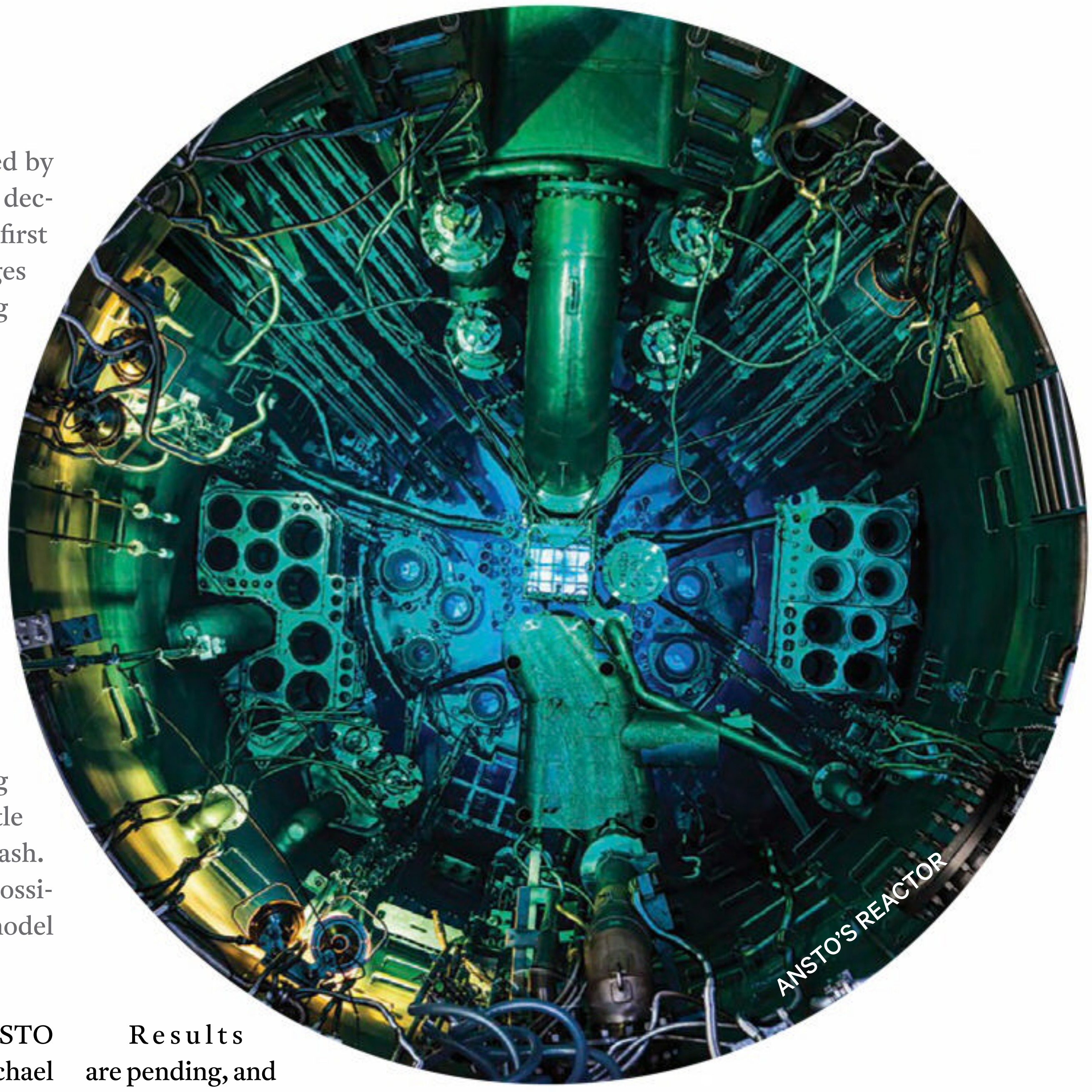
They've also set up a bunch of extra sensors to pick up other potential influences, like temperature or magnetic fields. And to make sure they've got it all right, they brought in the big guns.

"We're working with the National Measurement Institute," Streed says. "They're the timelords of Australia."

UNTIL LESS THAN a century ago, people believed that the continents were permanent features of the planet's surface. We live, they thought, on a static planet, where everything was and will be the same as it is now.

And yet earthquakes rock the land beneath our feet, volcanoes erupt with explosive force, and mountains rise thousands of metres above the surface.

Then, in 1912, a young German meteorologist called Alfred Wegener proposed that we live on a restless Earth. Building on ideas that had been floating around for 400 years – and his own observations that the coastlines of South America and Africa fit together like jigsaw pieces and have strikingly similar fossils despite being separated by the ocean – he put forth his theory of continental drift, arguing that the Earth's landmasses were once joined in a single supercontinent that had since broken apart.



Wegener's theory was summarily denounced by other geologists. Fierce debate ensued, but the decades rolled by and the data rolled in. Geologists first discovered ridges of underwater mountain ranges in the middle of oceans, then found alternating patterns of magnetic anomalies in rocks under the Pacific: evidence that the Earth's magnetic field has switched many times through history. In the early 1960s, a team from Cambridge pieced these ideas together to propose that magma from beneath the Earth's crust flows out through rifts in the seafloor at mid-ocean ridges, causing the seafloor to spread apart. As it cools to rock, the magma "freezes" in evidence of the Earth's magnetism.

An updated version of Wegener's continental drift – plate tectonics – suggests that the Earth's crust is indeed made up of interlocking plates, floating atop of the planet's active mantle that drives the plates to drift, rift, slide and crash. With this model, the Earth makes sense; it is impossible, now, for geologists to work within the old model of a static planet.

The caesium clock experiment at ANSTO had a personal timelord: NMI's Michael Wouters.

"We look after the standards for time and frequency in Australia, so we have an atomic clock that is the official reference for time of day in Australia," Wouters explains modestly.

In fact, NMI has five caesium clocks at their facility at Lindfield, Sydney, three of which are literally being used to keep time for the country.

"You know, there's the standard joke about time: if you have one clock, you know the time; if you have two clocks then you don't because they don't agree with each other," Wouters says. "That's one of the characteristics of clocks – you can measure them so well that they never agree with each other… So you need to have more than one to keep an eye on what's going on."

He and Streed had previously worked on a microwave atomic clock using the element ytterbium, and Wouters was keen to collaborate again.

"I pulled two caesium atomic clocks out of our ensemble for the experiment – something like that costs about $140,000 each, so you can't casually buy one," Wouters says.

He is quick to add that any problems with the remaining clocks would have caused the two to be recalled. But in the absence of a national time emergency, the clocks remained at the OPAL reactor from late December 2020 to early June 2021. Trillions of neutrinos zipped through them, and the speeds at which the clocks ticked were monitored scrupulously.

Results are pending, and the team is cautiously keeping expectations at a simmer. If this experiment comes up empty, then perhaps they either need more neutrinos, or better clocks.

See, Vaccaro's theory proposes a T violation background field. This is conceptually comparable to the Higgs field – an invisible force field, mediated by a subatomic particle discovered in 2012, that permeates all of space and gives other particles mass. Without this background field, life as we know it wouldn't exist; matter would simply flow ghost-like through the universe, as insubstantial as light.

Similarly, Vaccaro says that "even without mobile sources of T violation [like neutrinos], there is T violation there already, everywhere, pushing everywhere into the future".

This background field has to be uniform – with some local differences – based on our observations of time, but we have no idea how strong it might be.

"The local variation that's produced by the nuclear reactor could be very tiny compared to a background which is enormous," Vaccaro muses. "We're only changing the background by a tiny amount [with neutrinos]… If we only changed it by, you know, the 20th decimal place, then we need clocks that are accurate to the 20th decimal place."

The commercial caesium clocks used in the experiment are based on microwave frequencies and are good enough to keep time for the whole country, but Wouters says that if he could have dreamed up this

ANSTO

experiment with any kind of clock, it would be an optical one.

"The higher the frequency, the more precisely you can determine what one second is," he explains. "So for the microwave clock, the frequency is at about 10 gigahertz…whereas for an optical frequency, it's about 1014, Hertz, about 10,000 times higher.

"Basically, we could do the experiment about 10,000 times better."

But Vaccaro thinks that even with a microwave clock, the experiment was still worth trying.

"It's like if you're walking along, and you find this little rock that looks a bit different from all the others," she says. "You realise it's a fossil, and people walking beside you say, 'Oh yeah, it's just a tiny thing' – but underneath the Earth is a huge dinosaur, when all you're seeing is a little bone.

"And you never know, right? That little unusual-looking rock, you've got to investigate it, you've got to dig it up, see if it's connected to something else."

IN JUNE 1988, NASA climate scientist James Hansen testified before the US Senate Committee on Energy and Natural Resources.

The soft-spoken Hansen told the committee members "with 99% confidence" that rising global temperatures were not a natural fluctuation – that they were caused by carbon dioxide and other greenhouse gases emitted by human activity.

"It is time to stop waffling so much," he said. "The greenhouse effect has been detected and it is changing our climate now."

Along with forecasting that 1988 would be the warmest yet on record, Hansen outlined new research that projected future climate change under three different emissions scenarios. The second predicted that global temperatures would rise by 1°C by 2017 – a scenario that has played out with terrifying accuracy.

According to the US National Oceanic and Atmospheric Administration, 2021 was the sixth warmest year on record. Nine of the top 10 have occurred in the last decade. The year of Hansen's testimony, 1988, sits at 28th.

We have entered a confronting new era.

In January 2021, an international team of 17 ecologists published a perspective paper entitled: "Underestimating the Challenges of Avoiding a Ghastly Future."

In it, they lay out what we have already lost. Humans have altered a full 70% of Earth's entire area, both land and ocean. Many ecosystems have been dramatically reduced – wetlands by 85%, kelp forests by 40% – and wild populations of animals have declined by an average of nearly 70% in the last 50 years alone. Today, livestock and humans combined make up 95% of all terrestrial vertebrates.

"The scale of the threats to the biosphere and all its lifeforms – including humanity – is in fact so great that it is difficult to grasp for even well-informed experts," the ecologists write.

"The gravity of the situation requires fundamental changes to global capitalism, education, and equality, which include *inter alia* the abolition of perpetual economic growth, properly pricing externalities, a rapid exit from fossil-fuel use, strict regulation of markets and property acquisition, reigning in corporate lobbying, and the empowerment of women."

Climate science doesn't need a paradigm shift, but climate change needs a kind of societal Gestalt shift: to see, from within our current world, that another world is possible.

> "I'm talking about a really big story about physics, right? For one individual to be stirring the pot and see this coming out, it's just too much.

Near the end of our long, winding conversation, spanning symmetry and sigmas, flavours and time flow, Vaccaro tells me that her theory of time is nowhere near finished.

"I won't tell you more about it because I just have visionary things, you know – my imagination can be a wild thing," she says.

I have to agree. Her ideas are not just ambitious, but downright brain-breaking.

"You don't often get opportunities like that," Vaccaro says. "People work within a paradigm and the rules are well-established, and you do exciting things – but not as creative as this.

"The equations told me. I sound like a weirdo, but I had expectations about what I was going to do, and it wasn't anywhere near as much as what I found. It's just that you find certain results, and you think *it just doesn't make sense*. You have to change your perspective."

Vaccaro often thinks that it can't be *her* doing this potentially field-changing work. But at the same time, it's a privilege.

"It's a question of nature," Vaccaro says. "We know that T violation happens – it's verified by experiment. Is it the mechanism that gives us the experience of time that we have in our everyday experience? It's very rare to be able to ask such a big question in physics – there's only so many questions that you can frame in such a way."

And she's open to the fact that even if T violation is observed in the experiment, there might be a different explanation for it.

"What I hope to have done – even if I'm on the wrong track – is to open the door to taking another look at nature in a different way."

These days, I've let the universe flow out of my head. I still dream, sometimes, of what the Higgs field might look like, or how gravitational waves would shiver through me if I could feel them, but my brain doesn't have the space to try and grasp the velvet infinity of an edgeless cosmos.

Instead, my head is full of climate and biodiversity crises. Decades of measurements and modelling have recorded what is lost and what is still to come, but when I read this solid science, these hard numbers, I feel that same slipperiness as when I was 10: I can't hold their vastness in my brain.

In some senses I'm still tucked neatly into that rectangular prism of my childhood bed, still snug beneath the doona. Like most Western middle-class humans, I live in a house, with a job, a community, a set of societal expectations, a particular economic and political system. I sometimes feel like I've poured myself into a mould and forgotten everything but the shape of it.

My perspective only shifts when I step out of these structures and into the mountains, the islands, the forest, the desert. Here, I'm filled with the conviction that nothing matters more than my relationship to the Earth: that we don't just live on this planet, but are part of it. When present in this more-than-human world, this seems to be the single most important thing to know.

And yet, I forget. Back in my every day routines, those revelations – once so clear and present and forceful – become muffled, as if a doona has been thrown over them.

But we can't bury other realities if we want to shift the world on its axis, as we must. Instead we need to hold in our heads both worlds: the one composed of humans, and the one in which humans are only a small part.

It's not impossible. Science has rewritten the world time and time again, and each revolution has been confronting, each a time of distrust and debate. But countless times we have changed our worldview, both large and small – from accepting a universe in which we are not the centre to realising that the atom is not, in fact, the most fundamental building block of matter.

Our models of reality have been challenged by the dreamers, the re-inventors, the ones who follow their intuition beyond the comfort of the known. There is Copernicus, rewriting the dance of the planets around the Sun; there is Wegener, imagining an Earth where no pebble or mountain or continent is eternal; and perhaps there is Vaccaro, letting the equations lead her to a different conception of time – if we have enough time left.

First seen as crackpots or eccentrics, these people can become perspective-givers, showing us that it is possible to see both the vase and the two human faces at the same time. To them, the faces exist within a larger world – but if they're the whole picture, then the faces are gazing only at reflections of themselves. ⊙

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LNM / GETTY IMAGES

A TOUCHING T

Feeling small? It's on any scientist's wishlist, from physics to medicine and materials. **MARK PESCE** explains a new Australian innovation that can get a close-up view at a truly nano-scale.

Have you ever felt an atom? Being made of atoms ourselves, we are always in contact with them, both in our own bodies and in every aspect of the physical world. But we don't feel them, per se. Even when you lay your palm on the top of a table, you're not actually feeling atoms – you're feeling the repulsion of the electrostatic field created by the electrons that whiz around the periphery of every atom at speeds approaching that of light. They create a negative charge that prevents other atoms – also possessing negative charges – from getting too close together. At that level of detail, the whole world of "hard" surfaces becomes something akin to unthinkable numbers of tiny same-pole magnets trying to jam themselves together. They can get close – but not too close.

The physics of the "untouchable" atom opened the door to the first real attempts to be able to "feel" matter at the atomic scale. In 1981, Gerd Binnig and Heinrich Rohrer, researchers working for IBM Zürich, developed the "scanning tunnelling microscope" (STM). Built upon one of the basic effects of quantum mechanics, the STM places what is, in essence, the very sharp tip of a pin very close to a material being examined. When given an electric charge, electrons "jump off" the probe tip and "tunnel" through the material. The pattern of that tunnelling – where and when the electrons leap from tip to material – gives you an image of the material, much as if it had been shot through by an X-ray. Although atoms can't get close together, Binnig and Rohrer harnessed quantum tunnelling to allow them to ever-so-gently graze one another – research that won them the 1986 Nobel Prize in Physics.

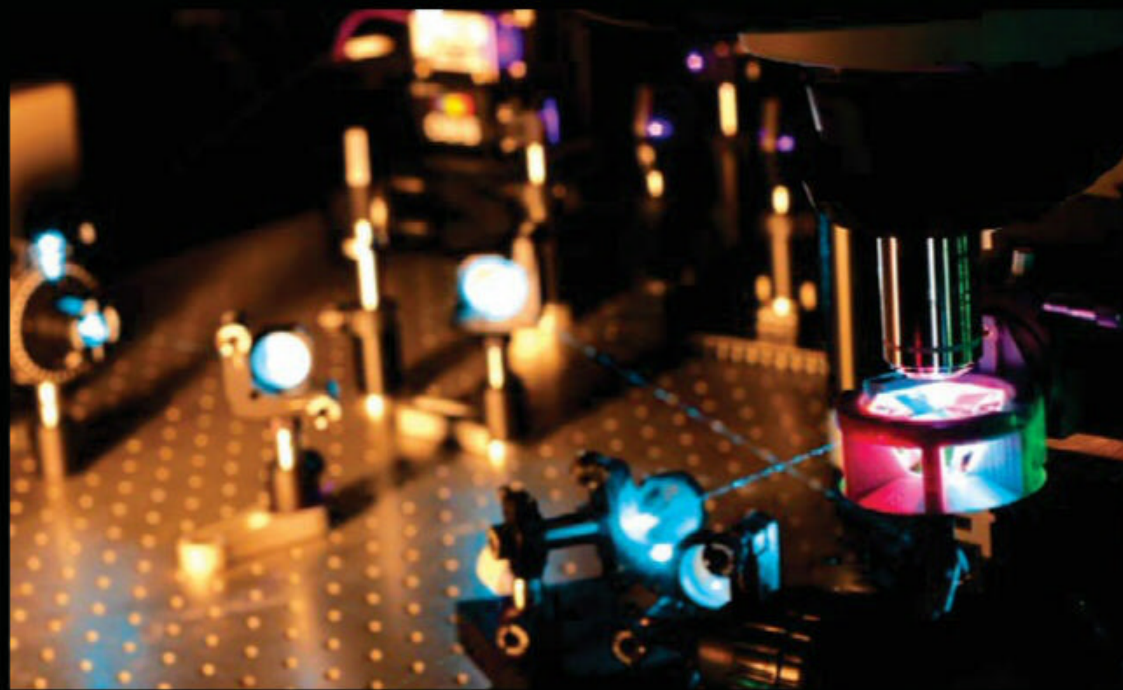
In 1985, Binnig went on to create the first real improvement in the STM – the "atomic force microscope", or AFM, which added a micromechanical vibrator to the tip of the probe. As the tip of the AFM vibrates back-and-forth, it scans an area of a material at the atomic scale. This tip – just a few millionths of a metre in length – could both "read" the material beneath it, and (with the addition of the appropriate electrical charge) even be used to push that material around, gently nudging individual atoms into new positions. To demonstrate their newfound capability, in 1989

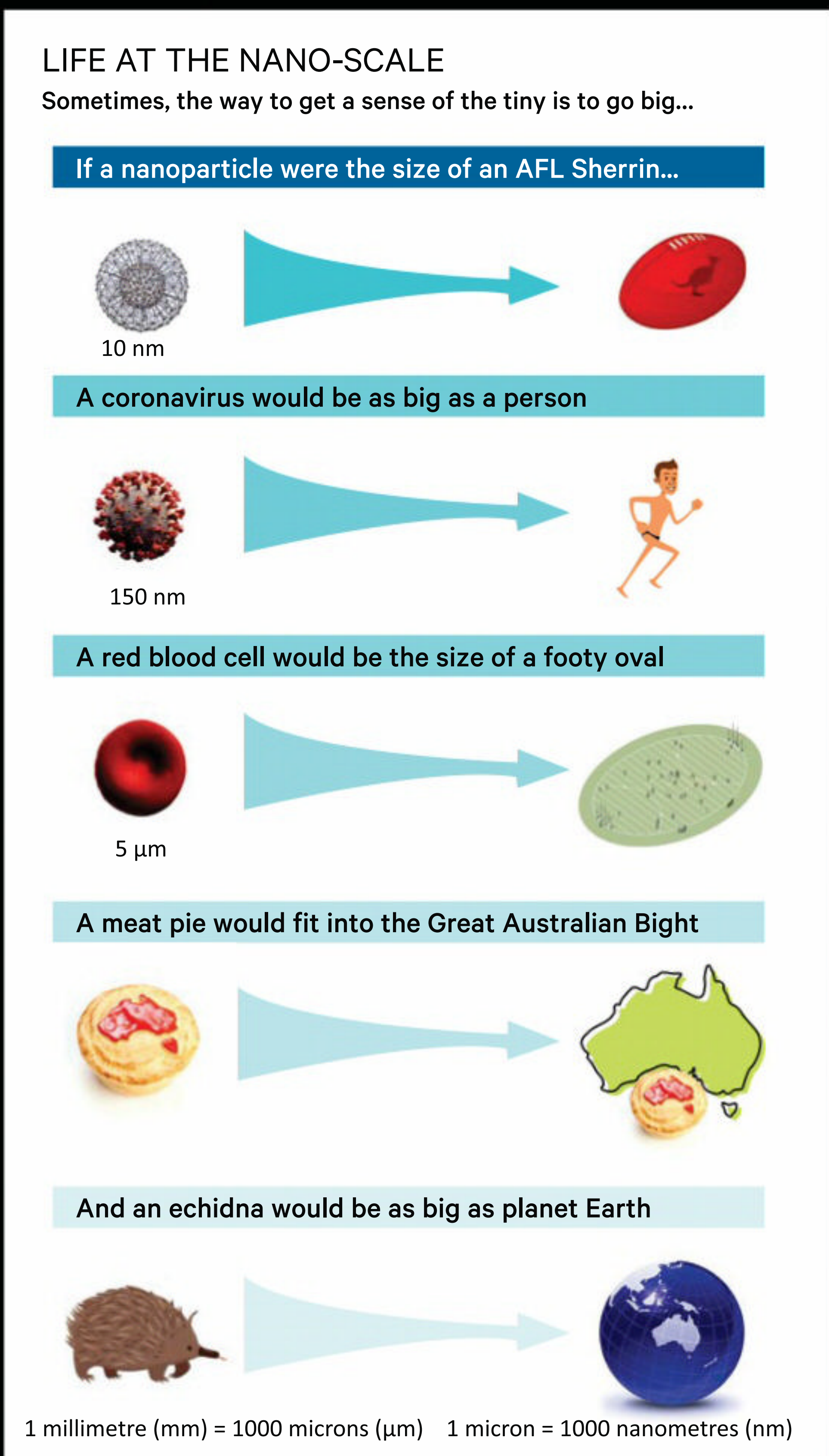
IBM released a famous photo of a set of xenon atoms arranged to form IBM's logo. This was no easy feat – the same quantum effect that allows electrons to tunnel from tip into material also made it terrifically easy for those atoms to "wander" away from the positions they'd been coaxed into by the AFM.

Atomic force microscopy made it possible to both "read" and "write" atoms, but it took a very clever graduate student at the University of North Carolina, US, to work out how to touch them. Russell M. Taylor fed the information generated by an atomic force microscope into a multi-million-dollar graphics supercomputer (which, given this was back in 1993, was almost certainly less powerful than your average smartphone), using that data to generate a three-dimensional "contour" of the material under the probe tip. Although images generated from AFM scans had given a rough picture of the "shape" of atoms, Taylor's visualisations offered a sense of depth, placement and orientation – not just a single atom, but this atom in relation to that atom, revealing the structures of chemically interlinked atoms (molecules). Projected onto a surface the size of a table, and viewed with special 3D glasses, these atoms and molecules looked as real as apples and oranges.

Taylor added one final touch to his research device – his VR system had a haptic interface; that is, it could deliver a faux sense of "touch" to the objects displayed within its tabletop virtual world. You could run your hand (virtually) across the surface of atoms, even push them around and feel them snap back into place. This Nanomanipulator, as Taylor christened it, became one of the landmark works of the first age of virtual reality. Sharing his work with some research chemists, they found themselves amazed that they could "feel" their way across chemical bonds and molecular structures that had always been theoretical abstractions, discovering things they never could have known about these substances, because their sense of touch revealed details no-one had ever even thought to intuit. Involving multiple senses, the Nanomanipulator made the atomic scale tangible, and gave chemists an incredible tool for thinking about their work.

But the Nanomanipulator was big, expensive and delicate. STMs and AFMs require a degree of precision and support that puts them in the rarest bits of laboratory kit – and even if you could get access to one, you'd still need a million-plus dollars of supercomputer to turn it into a Nanomanipulator. Taylor had crafted a breakthrough one-of-a-kind tool. Even preparing a sample for an AFM scan required considerable work; AFMs' and STMs' subjects must be placed into an isolated vacuum chamber – which immediately rules out the atomic-scale observation of anything even remotely alive. With the exception of tardigrades, vacuum and life don't mix.





An accidental discovery made in a laboratory at the University of Melbourne by researcher Christopher Bolton opened a less toxic window onto the nanoscale. In his work with lasers, Bolton saw something he'd neither seen nor heard of before – illuminating something microscopically small from multiple angles produced multiple views of the same object, and Bolton could use a bit of maths to sum those images together into a single view of that Very Small Thing.

As Bolton tells it, the story begins towards the end of his undergraduate studies, when he wound up in the lab of his research advisor Ray Dagastine, where he spent a couple of years "sort of percolating on ways to study how nanoparticles – nanotubes, viruses, things about that sort of scale – how they move and dance and interact with surfaces".

The pair played with a technique called general reflection microscopy and "spent a long time looking at spheres". Then they wanted to learn how are things that aren't spheres dance near surfaces. "And, what we started asking was, what kind of tools can we use? What kind of tools are available?"

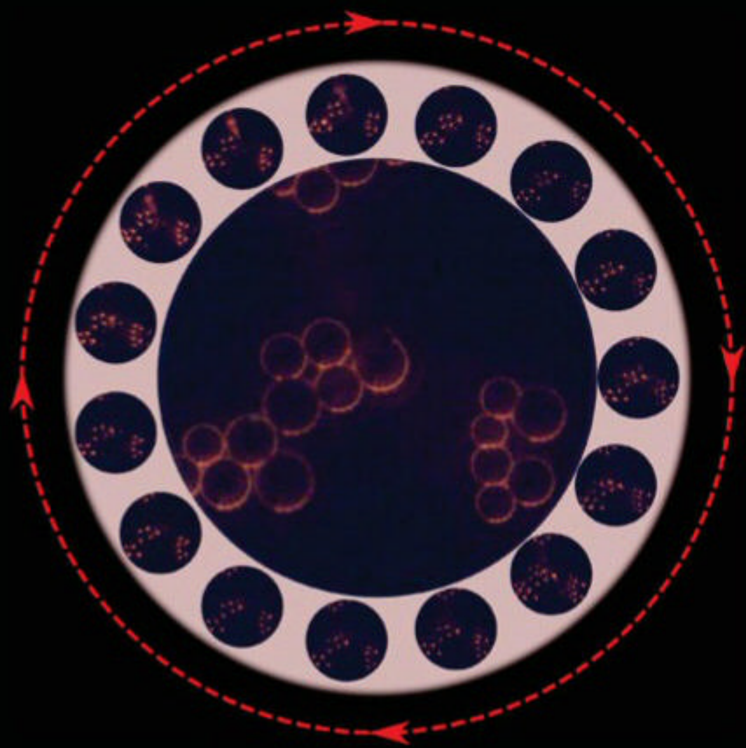
The search led eventually to the multiple illumination model, "some fairly complex mathy things to interpret the data" and – voila. "Through this complex math model, we can map out a direct reconstruction."

How small are the things they're looking at?

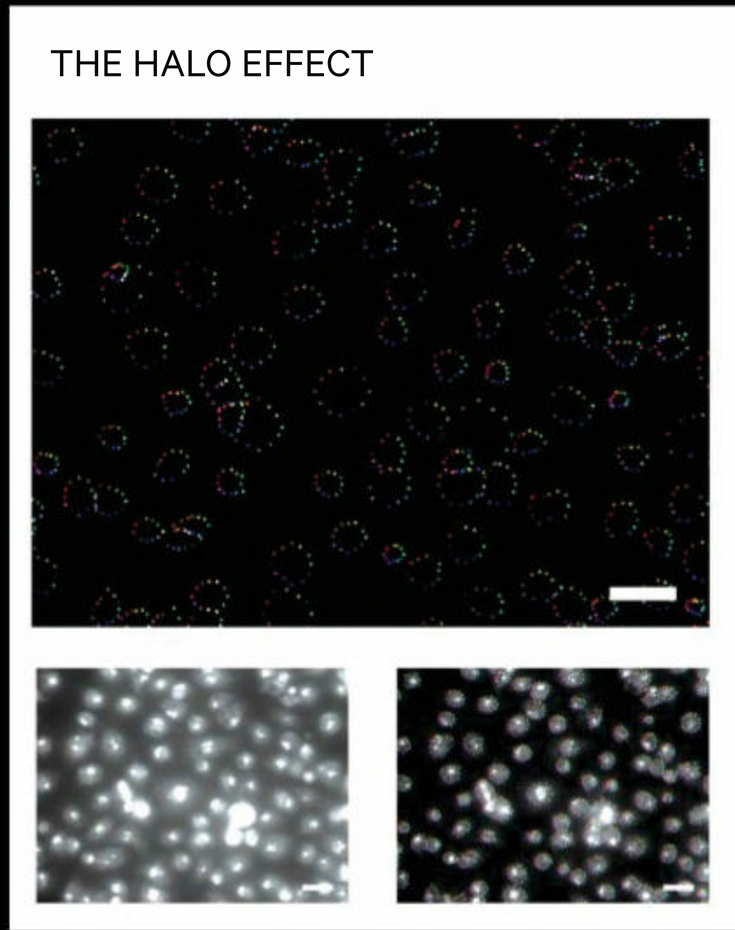
"The smallest thing we've looked at is about the smallest kind of virus that exists," Bolton says.

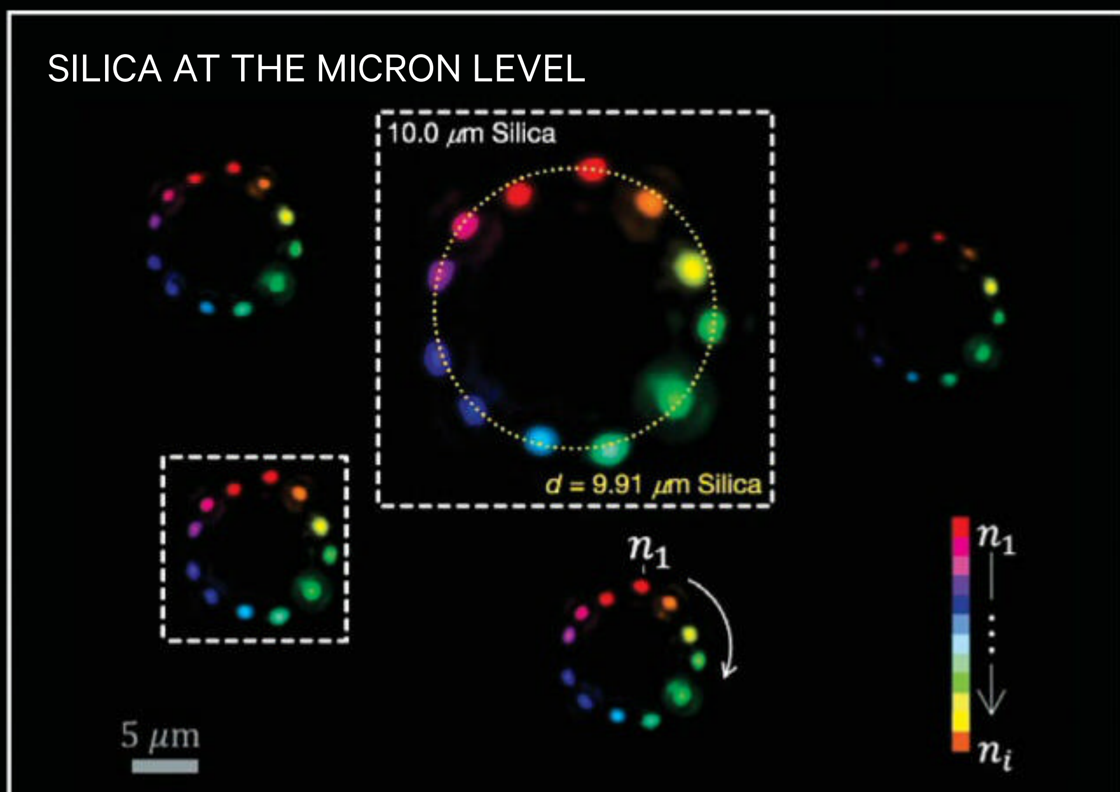
"The human eye can see down to about 100 microns, maybe a little smaller," explains Dagastine. "A human hair is 50 to 100 microns wide. A dust mite – which we can't see and are in our pillows – are kind of 10 microns-ish. Red blood cells are about five microns; we can still see that with a microscope.

(NANOPARTICLE) ALFRED PASIEKA, (SHERRIN) LOGORILLA, (MAN) GB_ART, (BLOOD CELL) SEBASTIAN KAULITZKI, (OVAL) DORLING KINDERSLEY, (AUSTRALIA) DENNY FACHRUL ROZZY, (ECHIDNA) EKATERINA ZIRINA, (GLOBE) LEONELLO CALVETTI / GETTY IMAGES



Illuminated by multiple lasers (opposite top), sample objects are captured in 15 shots in a circle (left), and then converted to an image by Tiny Bright Thing's patented Halo Vision. Different stages of image definition (right) include, at bottom left, bright field illumination; at bottom right, imaging in a Halo composite; and, top, 'overlayed', and ready for final-stage details for measurement (metrology). [Scale bar is 10 microns]





"The coronavirus is about 150 nanometers. … And the smallest thing we've looked at is about 25 nanometers. So that's 1/6th the size of the coronavirus."

The technique works with pretty much any sample they wanted to throw on a microscope slide – no vacuum necessary.

"We put a living bacterium on a slide," Bolton says, "and watched it as it struggled. When it died, it spilled its nanoscale guts onto the slide – and we could see those too!" These were the sorts of events that biologists had theorised about, but have never been able to see happening.

Bolton and Dagastine have turned the discovery into startup Tiny Bright Things. What's it going to do?

"We have lots of ideas," says Bolton. "The thing that excites us, I guess, is we want the technology to grow beyond us. And we want to be surprised by the applications. The most obvious things for us are the things informed by our experience, right?"

Dagastine agrees that they both see applications based on their experience. "We both happen to be chemical engineers," he says.

"Chris has worked in ag chem. And I've interacted with minerals processing and pharma. We actually saw industrial applications as well, particularly in the characterisation of powders, or particles in water, depending on what it is.

"And then the pharmaceutical industry – they really care about the size and shape, but don't have great ways to measure it. And it's often how a great deal of their processing goes awry.

"There's a great article from about 2005 or 2006, when somebody did a sector analysis, and I think was about $A120 billion globally is what the pharma industry lost from process inefficiencies."

Four hundred years ago, the first microscopes gave us a window onto a world we had never even imagined. These latest microscopes open a new vista onto a world we understand in theory, but have never visited in practice. How much more will we learn when we see the dance of nanoscopic living beings? And how long until some enterprising graduate student slaps a haptic interface onto this new microscope, so we can touch the surface of a virus, feel its spike proteins, and perhaps learn better how to defend ourselves from them? ◉

MARK PESCE is a professional futurist and public speaker and host of the podcasts "The Next Billion Seconds" and "This Week in Startups Australia".

DATA61 / CSIRO

Drawing on memory

Underlying his panoramic talent, artist Stephen Wiltshire has a gift so rare that science struggles to make sense of it.

If an artist's true talent lies in an ability to help us see the world through fresh eyes, broadening our perspective and making the ordinary sublime, Stephen Wiltshire has ability in spades.

As his website puts it, Wiltshire "sees and draws. It is how he connects." The same source asserts that Wiltshire didn't speak until he was five. Then his class at a London school for autistic children went on a field trip. Back at school, he spoke.

When they came back, he spoke. "He said, 'Paper'," his sister, Annette Wiltshire, told *The New York Times*. "The teacher asked him to say it again. He said it. Then they asked him to say something else, and he said, 'Pen'."

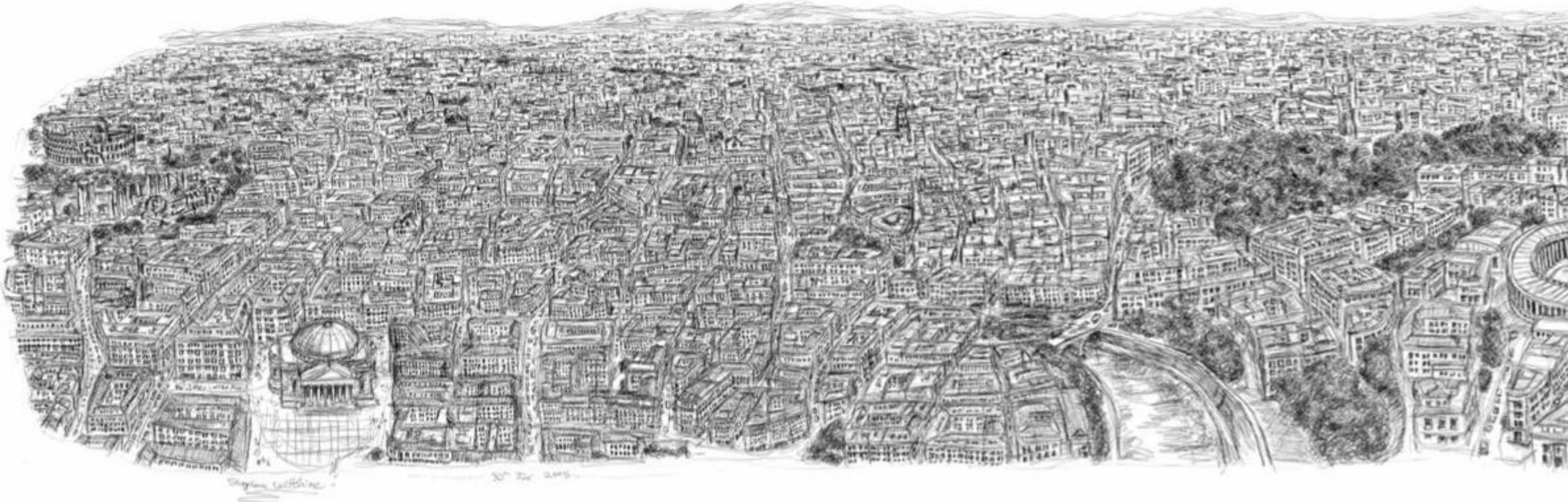
Wiltshire's intricately detailed renditions of cityscapes are astonishing in scope and detail – all the more so because they are done entirely from memory.

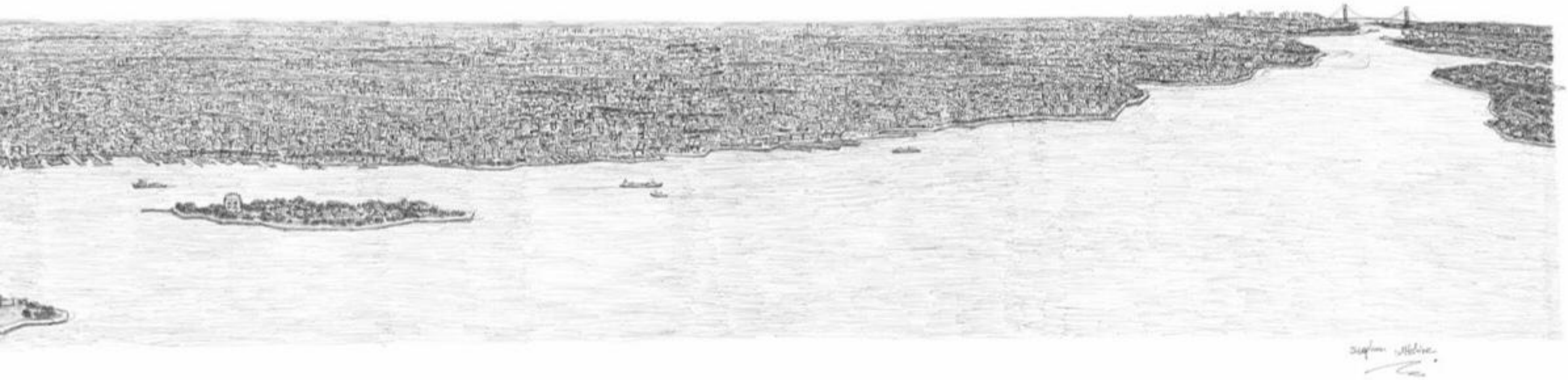
He's one of very few people known to possess an eidetic – or photographic – memory.

"Memory is at the core of what makes us human," says Dr Lucy Palmer, Laboratory Head at the Florey Institute of Neuroscience and Mental Health. "You could almost say it defines us."

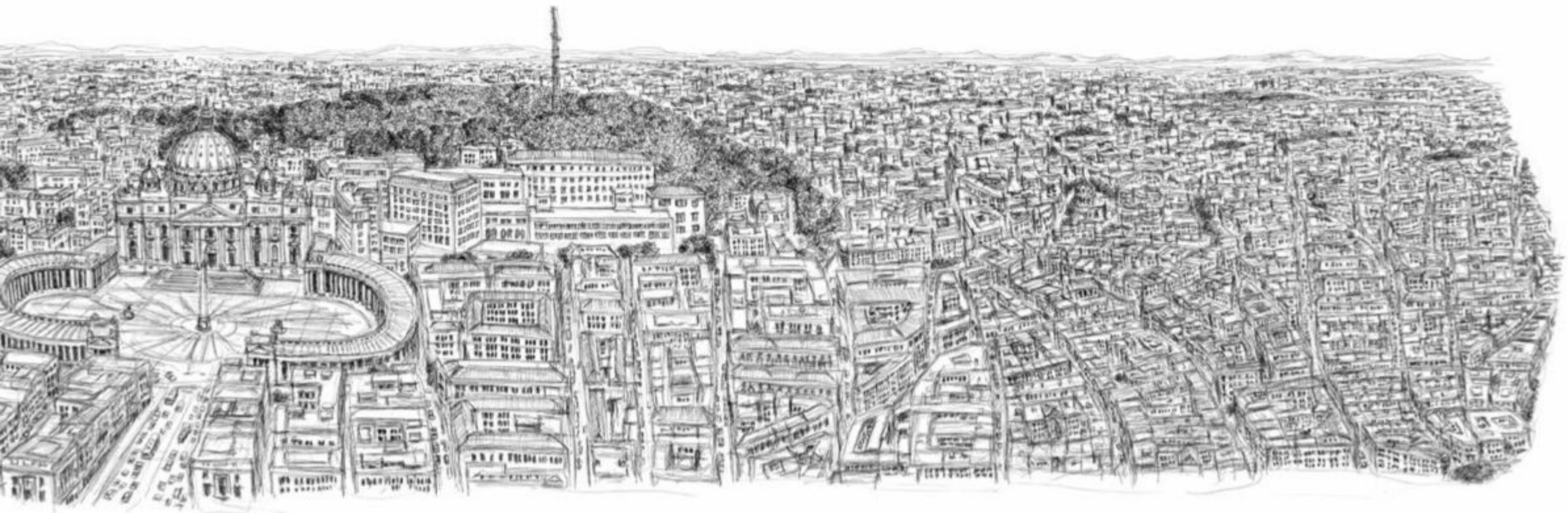
Palmer's laboratory studies memory by looking at changes in the activity of neurons during memory formation and recall, manipulating them to probe how and where memories are formed in the brain.

To prepare for this 5.8m-long intricately detailed panorama of New York City, Stephen Wiltshire took a helicopter ride lasting just 20 minutes. "I see the buildings and the skyline and see it from a bird's eye view," says Wiltshire. Back in the studio, working only from the memory of that sight, he recreated the city's 305 square miles (790 square kilometres) in five days. In the first four he'd captured most of Manhattan, several city bridges and Ellis Island, once the city's migrant gateway, which he's shown here rendering. "Section by section," he explains.

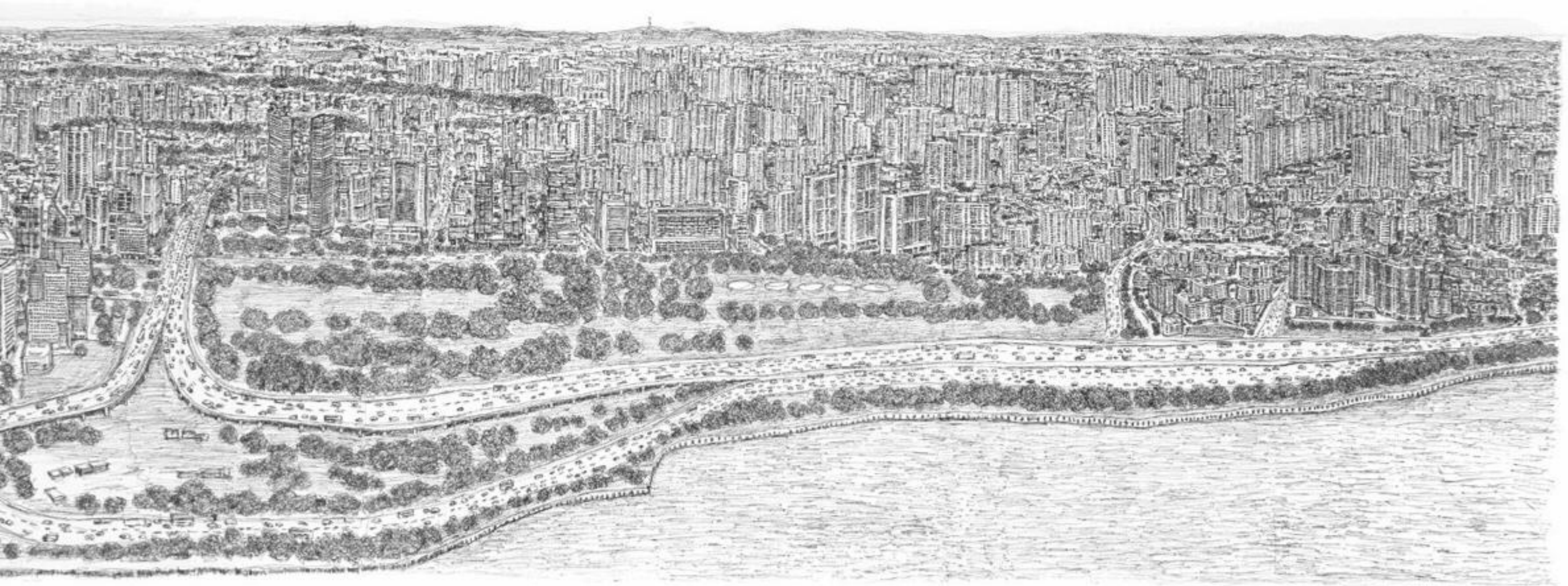




Of the completed New York panorama Wiltshire says: "I love the chaos and the order of the city at the same time, the rush hour traffic [versus] the square avenues."



Wiltshire's panorama of Rome was produced after a 30-minute helicopter ride, in which he insisted on flying over the Vatican and Saint Peter's Basilica repeatedly: little wonder they dominate the cityscape.



The government of Singapore commissioned Wiltshire in July 2014 to create a panoramic drawing of the city, to celebrate the nation's 50th birthday and become part of its National Collection. The resulting exhibition was seen by 150,000 people in five days.

She says that while memory capability varies across the human population, a photographic memory like Wiltshire's is so rare that there's little opportunity to assess and understand it.

"Photographic memory is thought to arise in a brain region called the posterior parietal cortex, that is specialised in receiving and integrating information from different pathways/senses," she says.

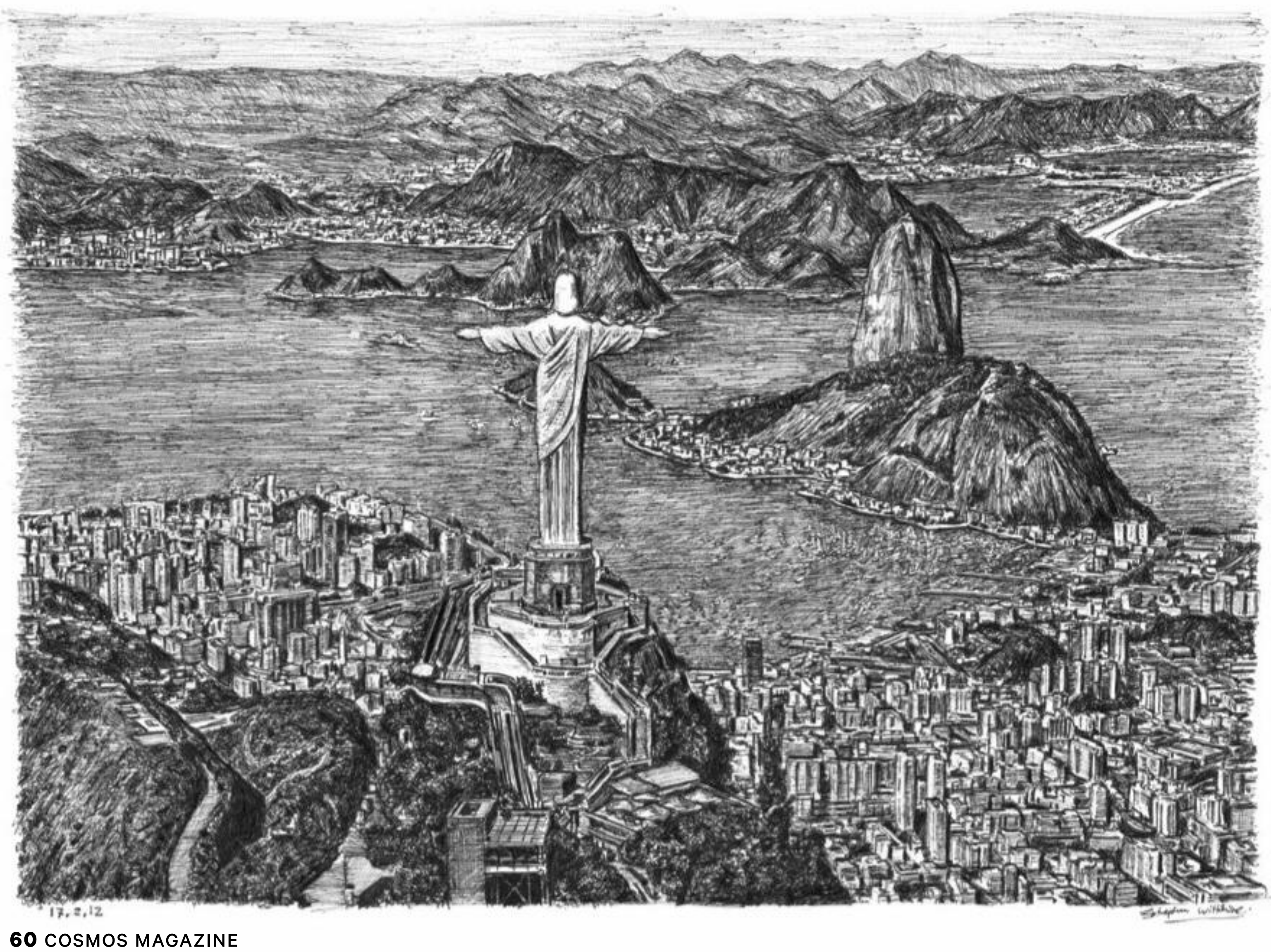
"We are still in our infancy in understanding how this cortical brain region works, but neurons within the posterior parietal cortex receive information from the parts of the brain dedicated to visual, auditory and somatosensory information. Perhaps in individuals that can perform photographic memory, the integration of these different sensory pathways are enhanced."

One thing is certain: Wiltshire's memory is a rare piece of processing kit.

Palmer says that for the vast majority of us, memory is a fine balance between remembering and forgetting. She explains that as we move through our lives, we don't always want or need to remember every aspect of the world around us.

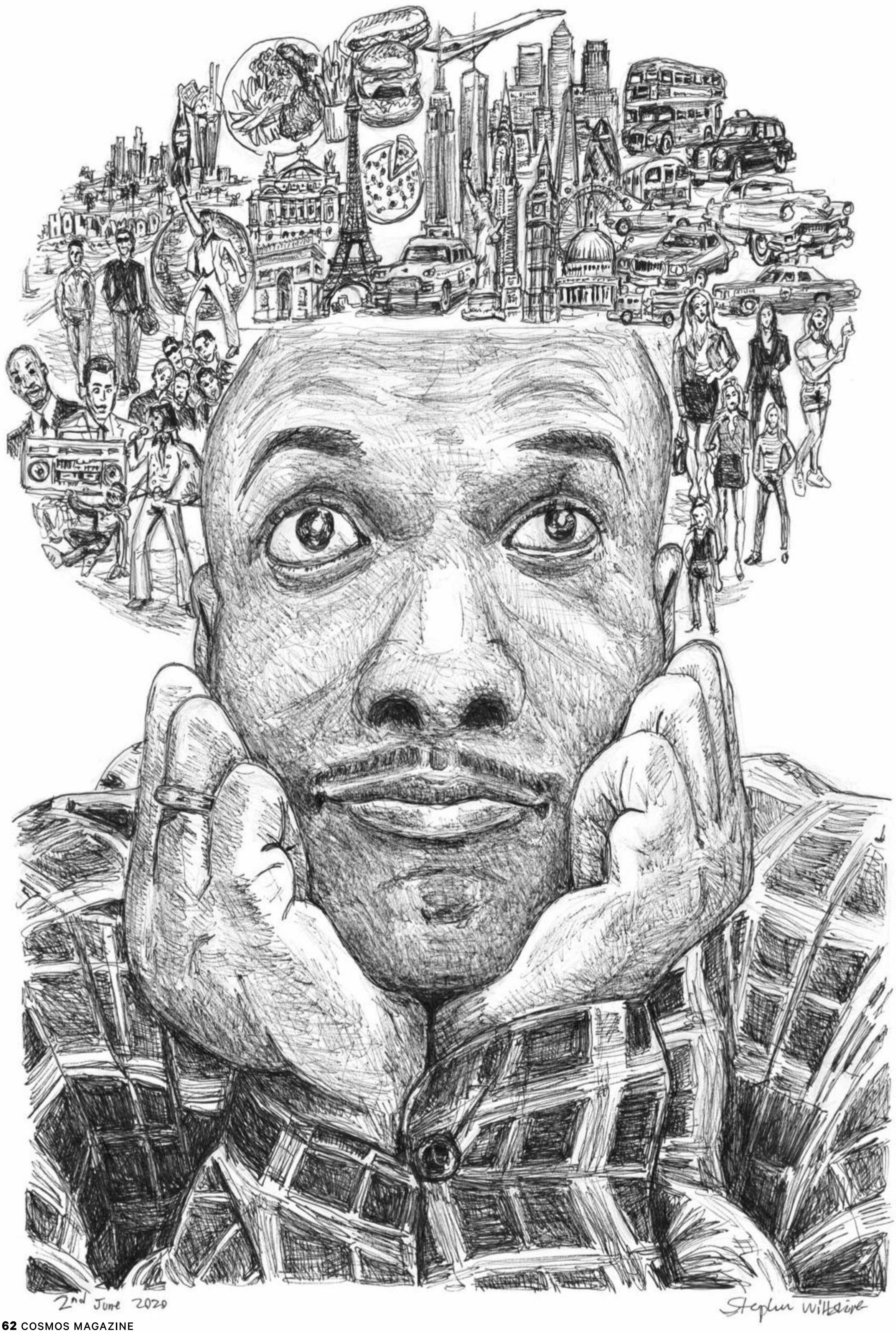
"Our brains are very good at 'filling in gaps'," she says. "We can clearly identify an image when we are only presented with a blurred picture. Perhaps this is because brain activity, and memory formation, comes at a cost. The brain requires energy to function, and where we can conserve energy, we will.

"We don't need to remember the number of trees on our walk to work and the cars that drove past us, but we do need to remember the roads that we must turn down."



These street views of (top) the Eiffel Tower and Arc de Triomphe in Paris; (left) Rio de Janiero; and (opposite) Fifth Avenue in New York perfectly illustrate Wiltshire's unique approach. "He cuts the drawing into segments, then fills each one in," says his sister Annette. "We will all see the same thing, but we focus on what is of special interest. For Stephen, it's like a sponge where he absorbs everything but he doesn't squeeze out the rest."


21st July 2020
Stephen Wiltshire.


HOLLYWOOD
2nd June 2020
Stephen Wiltshire

It would seem that Wiltshire's brain has opted for a different approach, processing the whole picture rather than stitching together disparate scraps.

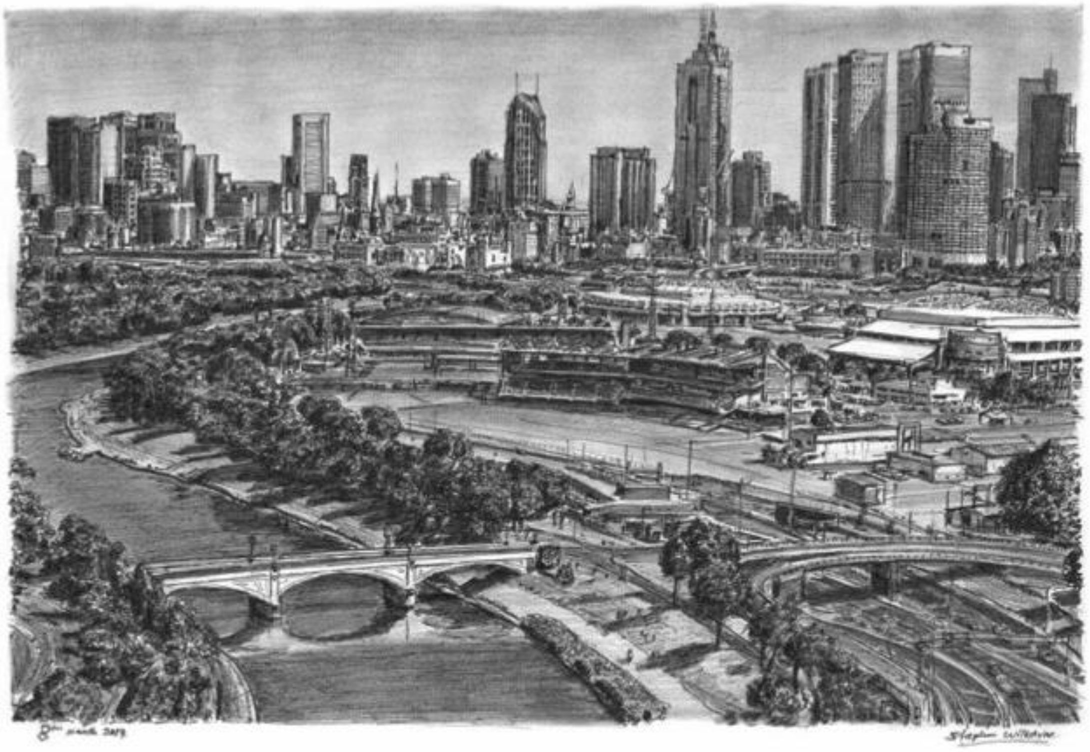
"Although it's not known, it is possible that those with photographic memory do not forget the parts that are not important to the overall memory."

While most of us will never possess Wiltshire's talent, Palmer says we do have the capacity to shape our brains to some degree.

"The brain is dynamic. It is changing from minute to minute, hour to hour. We can train our brains to have better memory – and the more we learn about how memories are formed, the more informed we are about how memories can be strengthened."

– Jamie Priest

To read more about Wiltshire and see other works, visit www.stephenwiltshire.co.uk



The Australian cities of Melbourne (above) and Sydney (below) are two of the dozen or more major world urban areas Wiltshire has drawn since 2005. "My thoughts" (opposite) is a rare self-portrait – his website says he "more often doodles everyday objects, people and ad hoc observations" privately. "Stephen has no understanding of autism," says Annette. "However he does understand that he is an artist, an artist in his own right and [should] not be labelled with this title. It's important to concentrate on his talent and how he has overcome his hurdles."

A remarkable global scientific "competition" is seeking to once and for all create a unified theory of consciousness. **JP O'MALLEY** talks to those trying to comprehensively define this ephemeral – yet fundamental – quality.

Illustrations by Greg Dunn

WILL WE EVER TRULY DEFINE CONSCIOUSNESS?

Consciousness has baffled philosophers since the days of Plato and Aristotle in ancient Greece. So it's helpful to start with some simple definitions. Consciousness is considered the central fact of existence: It's everything you experience. It gives you a sense of self. Consciousness is focusing on the present, remembering the past, and planning for the future.

The past two centuries of clinical and laboratory studies have revealed an intimate relationship between the conscious mind and the brain – although the exact nature of this relationship remains evasive.

"There is no question the brain is the organ of consciousness," Christof Koch explains from his home in the US. "And it's not the entire brain, it's bits and pieces of the brain."

The 64-year-old German-American neuroscientist is president and chief scientist of Seattle's Allen Institute for Brain Science, and a key mover in one of the most intriguing experiments imaginable.

Many scientists have proposed numerous theories on consciousness, all the result of independent research. So can a collaborative consensus be reached among the global scientific community as to how consciousness arises in the brain?

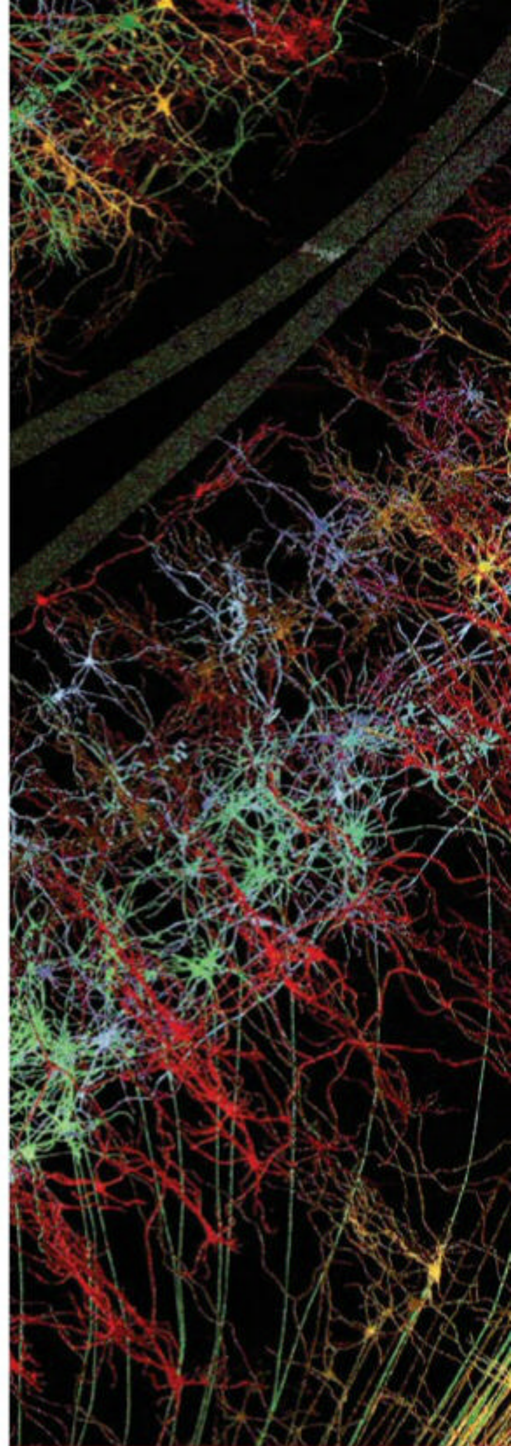
In 2018, Koch and a number of other neuroscientists had a meeting at the Allen Institute to address this issue. They came up with a practical solution: to run an adversarial collaboration competition between two opposing hypotheses on consciousness.

The Accelerating Research on Consciousness Initiative began in November 2020. The two theories going head-to-head are the integrated information theory (IIT) proposed by Giulio Tononi, and the global neuronal workspace (GNW), proposed by psycho-biologist Bernard Baars and neuroscientists Stanislas Dehaene and Jean-Pierre Changeux.

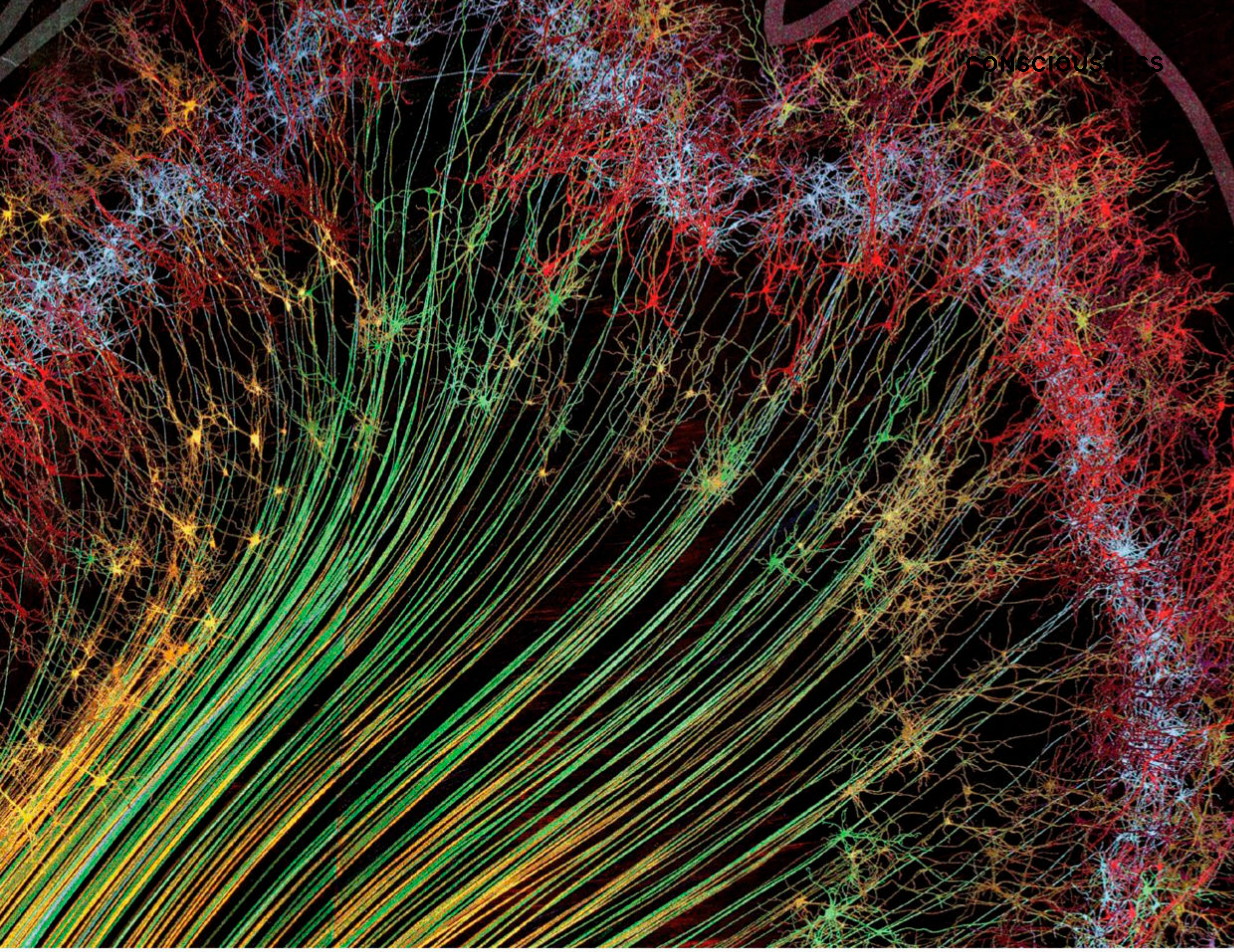
"This collaboration involves 12 labs, where the IIT proponents get together with the GNW proponents and hammer out a set of experiments in both humans and animals," Koch explains. "If the outcome goes one way, it'll support IIT, and if the outcome is another, it'll support GNW."

Led by neuroscientist Lucia Melloni, a professor at the Max Planck Institute for Empirical Aesthetics, in Germany, the three-year, US$20 million open science research program will combine invasive and non-invasive methods in its respective experiments, including functional magnetic resonance imaging (FMRI), electroencephalography (EEG), and magnetoencephalography (MEG). When the project is complete, all its data will be made available on a public server. "These experiments are bringing together different teams of people whose ideas about consciousness differ," Koch explains. "But we're trying to work together to resolve this with evidence in favour of one theory."

IN *THE CHARACTER OF CONSCIOUSNESS,* Australian philosopher David Chalmers first points to the *easy problems* of consciousness. These are



The neuroscientists' search for consciousness focuses on various centres in the brain, such as the visual cortex (left), the region located at the back on the brain that processes visual information. The parietal gyrus (above right) is where movement and vision are integrated.



Antonio Damasio
Professor of Neuroscience, Psychology and Philosophy, University of Southern California

RIGHT: WIKIMEDIA

phenomena that can be rationally explained by computational or neural mechanisms. Chalmers says they include such things as the ability to discriminate, categorise, and react to environmental stimuli; the reportability of mental states; the focus of attention; the deliberate control of behaviour; and the difference between wakefulness and sleep.

But then a murky metaphysical obstacle raises its head: the problem of logically explaining conscious experience. Chalmers has infamously characterised this as the so-called "hard problem" of consciousness.

The hard problem is especially tricky for any scientist seeking to explain an objective world with measured rational analysis. Philosophers refer to subjective properties of experiences as "qualia" – the sensory emotion evoked when hearing, say, Beethoven's *Symphony No. 5 in C minor*. Qualia also includes bodily sensations; the flow of conscious thought; mental images; emotions; tastes; and moods.

"You cannot understand what mind is at the level of consciousness if you don't incorporate feelings."

The hard problem poses many questions. How does one relate the first-person subjective account of experience to a third-person objective account? How do you explain the relationship between physical phenomena, such as brain processes, and experience? And how do you figure out why a given physical process generates the specific experience it does?

Philosophy's answers contain more paradoxical perplexities than clinical definitions. During the 20th century, behavioural psychologists became the gatekeepers of consciousnesses. But they stumbled upon the same metaphysical problems philosophy faced. Over the past three decades the most sophisticated empirical studies of consciousness moved into a neural domain.

CHRISTOF KOCH'S INTEREST IN CONSCIOUSNESS became a lifelong obsession in 1989 – following a detailed conversation with the late Nobel Prize-winning British scientist, Francis Crick. "The hard problem is ultimately a metaphysical proposition," Koch says, "not an empirical scientific truth. Francis and I said: 'Let's adopt a working definition of consciousness.' And by testing people, or a closely related species, we can look for the footprints of consciousness in the brain."

Crick and Koch sought to fully understand the minimal neuronal mechanisms jointly sufficient for any specific conscious experience, which they labelled the "neural correlates of consciousness" (NCC). By explaining the NCC in causal terms, Crick and Koch claimed the problem of qualia would eventually become clearer.

The NCC are typically assessed by determining which aspects of neural function change, depending on whether a subject is conscious or not. An operational definition of NCC largely comes from behavioural reports from patients with neurological psychiatric disorders, or brain damage from trauma.

Koch believes "it's absolutely necessary to study the material substrate of consciousness, [especially] mapping out the way things feel at the physical substrate and the structure of the brain." He explains how the brain itself could be considered an NCC —after all, it generates conscious experience every day. So trying to ring-fence consciousness down to specific brain regions is a trial-and-error process of elimination, he explains.

The spinal cord is a major part of the central nervous system that conducts sensory and motor nerve impulses to and from the brain. But when it's severed by trauma, tetraplegics continue to have full conscious experience. It's a similar story for the cerebellum, the "little brain" underneath the back of the brain that controls complex actions like walking and talking. When it's damaged as the result of a stroke, there is little effect on conscious experience.

"Most patients that have cancer tumours in the cerebellum say: 'I feel, see, and hear the same as before'," says Koch. "So the cerebellum doesn't seem to be essential for consciousness."

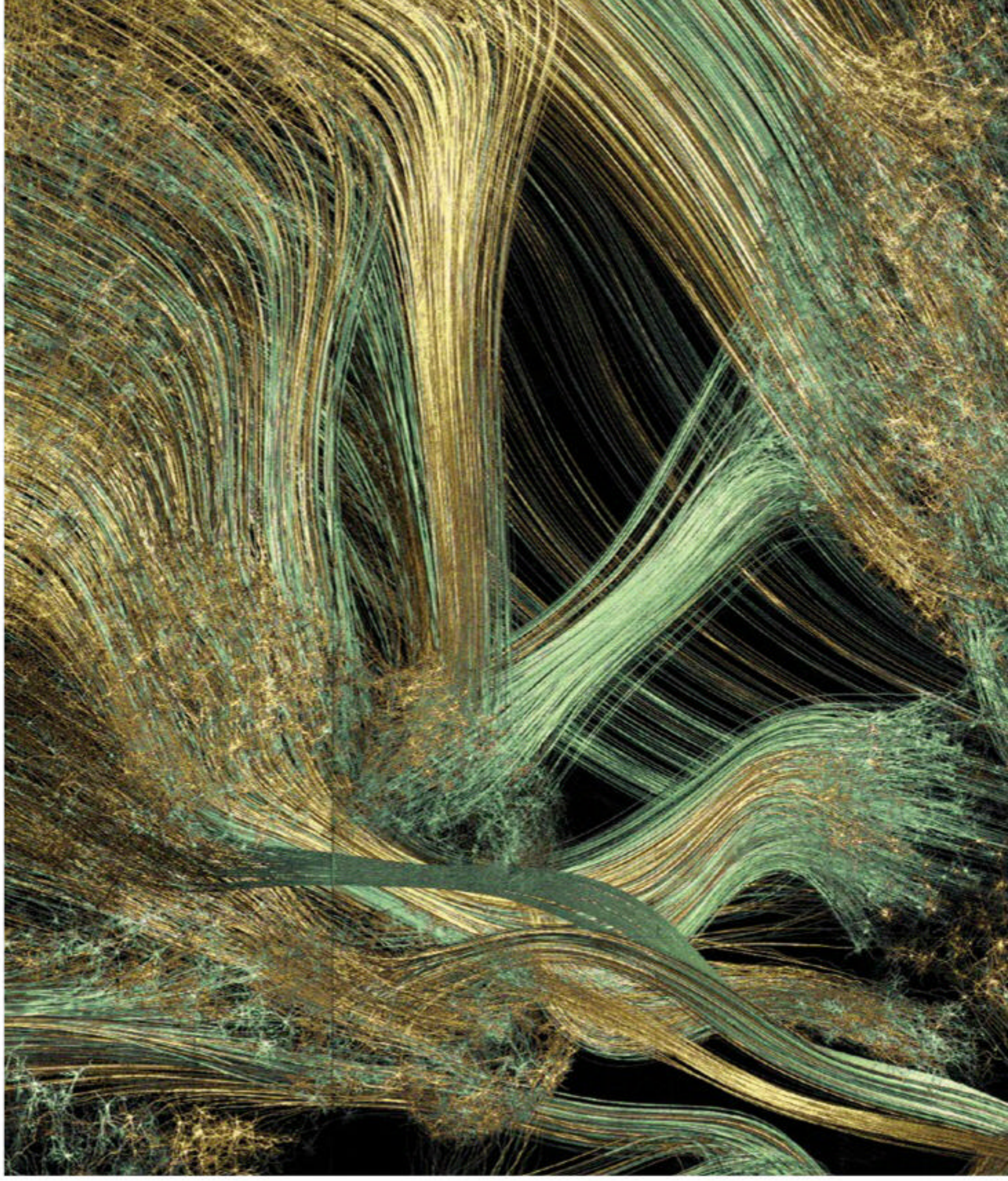
How about the brainstem – the structure of nerve tissue that connects the cerebrum of the brain to the spinal cord and cerebellum? "If you have a small stroke in the brainstem, you can be in coma, so the brainstem is essential for consciousness," Koch explains.

"But that's not where consciousness is happening. Because even though patients may have an intact brainstem, if they lose a large part of their cortex – particularly the back part of the cortex – they are not conscious. It's really the posterior region of the cortex that gives rise to specific content of experience. And if you lose specific regions of cortex, you can lose a sense of smell, or hearing etc."

Koch says there are experiments that can test for "a very primitive first-order conscious meter", and points to practical tools that assist in understanding the dynamics of the brain. The EEG detects electrical activity in the brain using small electrodes attached to the scalp; it measures the tiny voltage fluctuations generated by electrical activity across the neocortex, the brain's outer surface responsible for perception, action, memory and thought. Koch also mentions transcranial magnetic stimulation (TMS), a procedure that uses an insulated coil placed over the scalp – where magnetic fields stimulate nerve cells in the brain. TMS is generally used to improve symptoms of depression.

"In humans you can use TMS, because you want to get a causality [for consciousness]," says Koch. Nevertheless, some practical and ethical obstacles remain. "You can generally observe the human brain, but it's much more difficult to perturb it," he says.

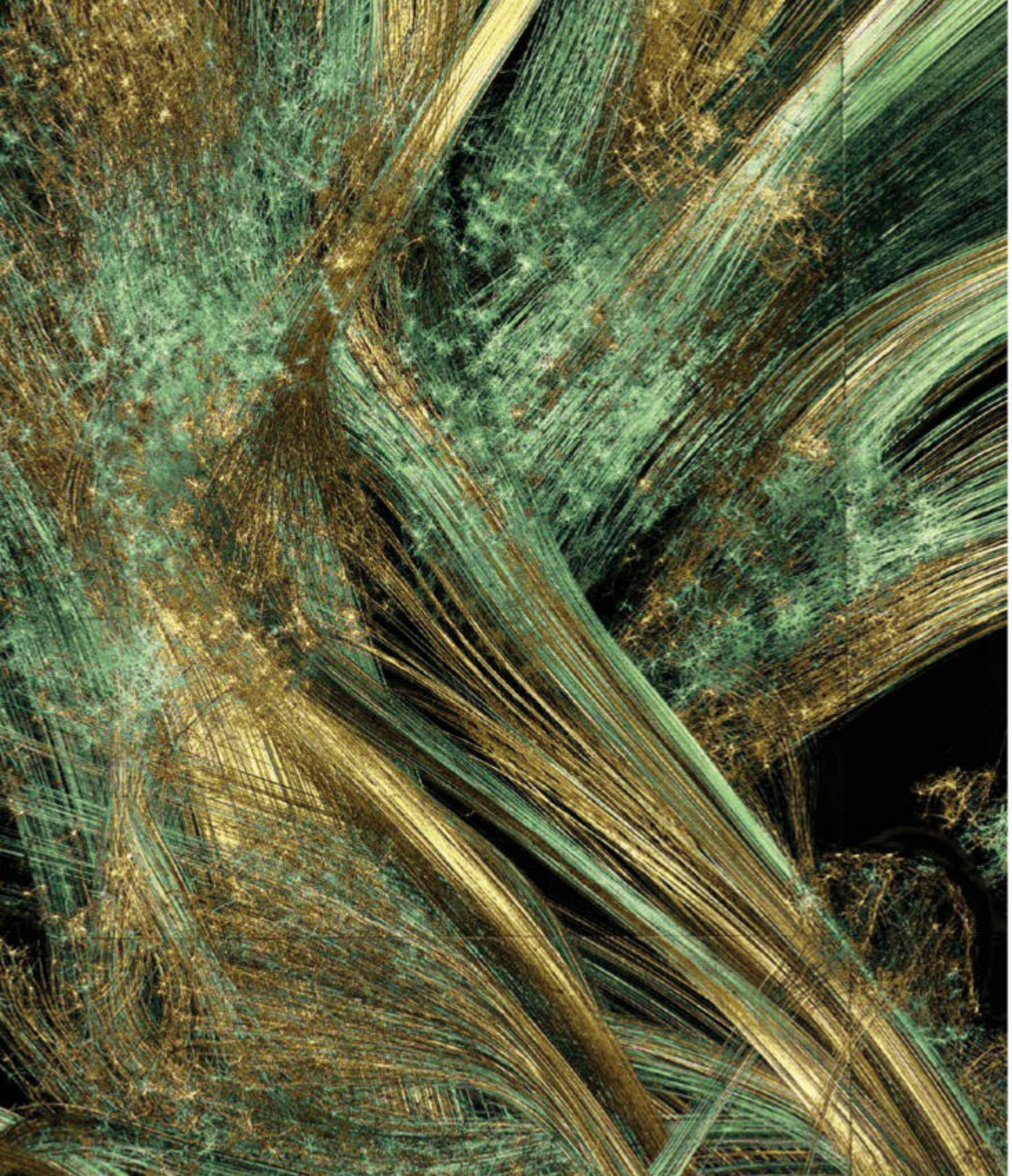
Testing the brains of rodents is one way of overcoming those ethical hurdles. The last common



Christof Koch president and chief scientist, Allen Institute for Brain Science, Seattle, USA

LEFT: ALLEN INSTITUTE FOR BRAIN SCIENCE

"By testing people, or a closely related species, we can look for the footprints of consciousness in the brain."



The thalamus and basal ganglia (above) is the area of the brain responsible for sorting senses, initiating movement and making decisions. But researchers are yet to determine if it is the seat of consciousness in humans.

ancestor of mice and humans goes back 65 million years. But the basic cortex structure in mice and humans is the same, Koch explains: "You can manipulate neuron populations with great precision in a mouse in a way you couldn't do with a human brain. This gives you basic knowledge that you can then take back into the clinic and manipulate on a monitor."

Such clinical and laboratory evidence is contributing to real progress in the continual quest to fully understand consciousness. But Koch maintains that a satisfying scientific theory of consciousness is needed – and it should predict under which conditions any particular physical system has experiences.

Cue the Accelerating Research on Consciousness Initiative.

KOCH HAD SOME INVOLVEMENT IN DEVELOPING integrated information theory: "IIT shares the view that consciousness may exist throughout the tree of life, and it may even extend to non-biological and non-evolved physical systems."

But IIT is really Giulio Tononi's brainchild.

"The theory starts out by saying: out of nothing, suddenly there is your experience," the 61-year-old Italian neuroscientist and psychiatrist explains. IIT proposes the idea that consciousness is the ability of a system to integrate information, which provides an adaptive evolutionary advantage. The theory then states that every conceivable experience has five essential properties.

The *subjective* is experience that exists only for the subject as its owner. *Structured* says each experience is composed of many phenomenological distinctions, elementary or higher order, which also exist. *Specific* says each experience is distinct from any other conscious experience. *Unified* says an experience is one thing, not two. *Definite* says experience contains what it contains, not less, not more.

IIT then posits that any complex and interconnected mechanism whose structure encodes a set of cause-and-effect relationships will have these five properties – and thus will have some level of consciousness.

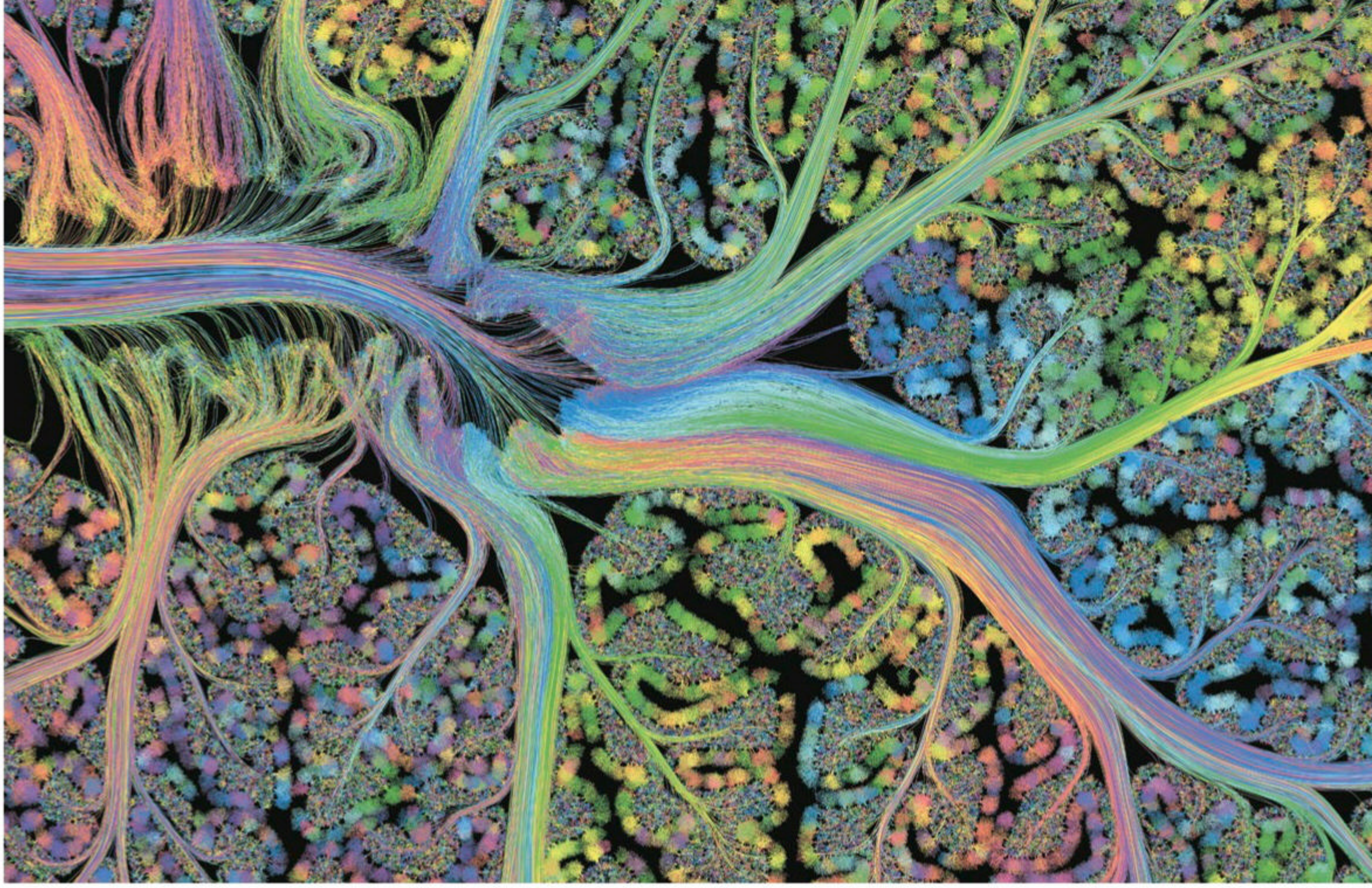
"IIT says whatever the substrate of consciousness is, it should satisfy those five properties in physical terms," Tononi explains. IIT also proposes that to be conscious you need to be a single integrated entity with a large repertoire of distinguishable states – this is the definition of information. Tononi says a system's capacity for integrated information – and thus for consciousness – can be measured. This is done by asking: how much information does a system contain above and beyond that possessed by its individual parts?

The quantity for measuring this is called Φ, or phi. Φ is a proxy for integrating information, and can be calculated, in principle, for any system. If Φ is zero, the system does not feel like anything to be itself. But as Φ increases, the more intrinsic causal power the system possesses, and the more conscious it feels. The brain has enormous and highly specific connectivity. It therefore possesses very high Φ, implying it has a high level of consciousness.

"The theory predicts that whatever gives you a maximum of Φ leads to a very precise prediction: maximum existence," Tononi explains. "So it's a principle that says: among competing existence, the one that exists is the one that exists the most."

Tononi's theory also addresses the issue of qualia. "This is often brought up as the hard problem of consciousness – why consciousness feels the way it does," he explains. "IIT says: this must be addressed in a scientific manner."

Tononi notes that conscious experience is spatially extended. He cites the example of looking at the sky at night: it just feels like one big extended canvas. "A lot of work IIT has done has tried to characterise the phenomenal properties of this extendedness [in experience]," Tononi explains. "We start with space. Then we look at time and ask: why does it feel flowing? We also ask: why do objects feel like objects? And we check whether this is supported by empirical data about which parts of the brain are responsible for us typically feeling extended in this



space." IIT also predicts that a sophisticated simulation of a human brain running on a digital computer will not be conscious. And since consciousness cannot be computed, it must be built into the structure of the system.

"If the theory is correct, computers are not going to be conscious: they are machines that will stay machines," Tononi says. He keenly stresses that IIT is built upon the foundational premise that "consciousness is about being, not doing" and that "information is a structure, not a function".

THE GLOBAL NEURONAL WORKSPACE (GNW) theory argues that consciousness is a function that broadcasts sensory information globally to multiple cognitive systems in the brain. GNW also posits that consciousness is a property of a cognitive system – and it processes information to generate conscious awareness.

GNW proponent Bernard Baars has been studying consciousness since the early 1980s. His research led him to come up with the original global workspace theory (GWT). It began as a purely psychological theory of conscious cognition, which sought to find a plausible answer to the question: how does a serial, integrated and limited stream of consciousness emerge from a nervous system that is mostly unconscious, distributed, parallel and of enormous capacity?

"Global workspace theory (GWT) is a very detailed implementation of the ancient idea of the theatre of consciousness," Baars explains. Today, it makes sense to talk about consciousness as "broadcasting in the brain web", the 75-year-old psycho-biologist and theoretician explains.

The term "global workspace" comes from artificial intelligence, where it refers to a fleeting memory domain that allows for cooperative problem-solving by large collections of specialised programs. GNW claims that consciousness enables a theatre architecture to operate in the brain, in order to integrate, provide access, and coordinate the functioning of very large numbers of specialised networks that otherwise operate autonomously. The network of neurons that broadcast these messages is hypothesised to be located in the frontal and parietal lobes. Once these sparse data are broadcast on this network, they are said to be globally available, and the information thus becomes conscious. GNW proposes that computers of the future will become conscious.

French neuroscientists Stanislas Dehaene and Jean-Pierre Changeux have subsequently built on Baar's original GWT theory. GNW has developed

Lucia Melloni project coordinator, Accelerating Research on Consciousness Initiative

> "This collaborative initiative is happening under the umbrella of open-democratic science"

LEFT: NYU GROSSMAN SCHOOL OF MEDICINE

experimentally testable models and made further testable claims about the brain basis of visual consciousness. "Stanislas Dehaene and Jean-Pierre Changeux have both built on my theory in a very beautiful way," says Baars.

But has the crusade to understand consciousness focused too specifically on brain anatomy? Professor of Neuroscience, Psychology, and Philosophy at the University of Southern California (USC) Antonio Damasio believes so. "Linking brain and body together" is paramount to really unpack the question the hard problem poses, the 77-year-old explains. "Consciousness is being generated by a variety of organism structures: some neural, some non-neural."

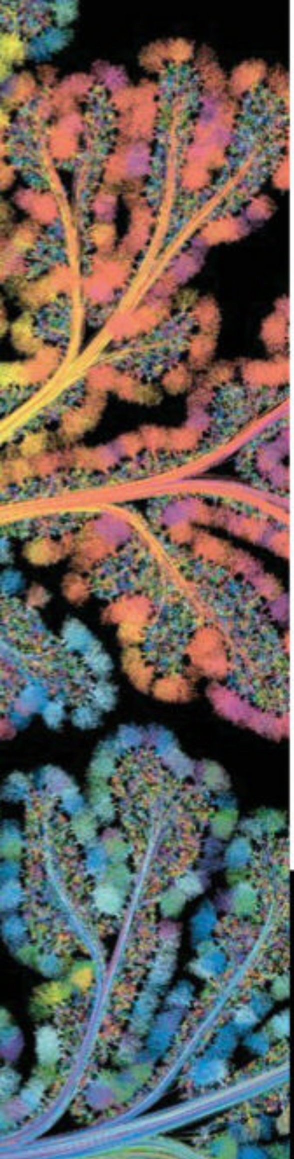
"You cannot understand what mind is – at the level of consciousness – if you don't incorporate feelings," Damasio adds. "The feelings that we have of hunger or thirst, or pain, or wellbeing, or desire etc, they are the foundation of our mind," says Damasio.

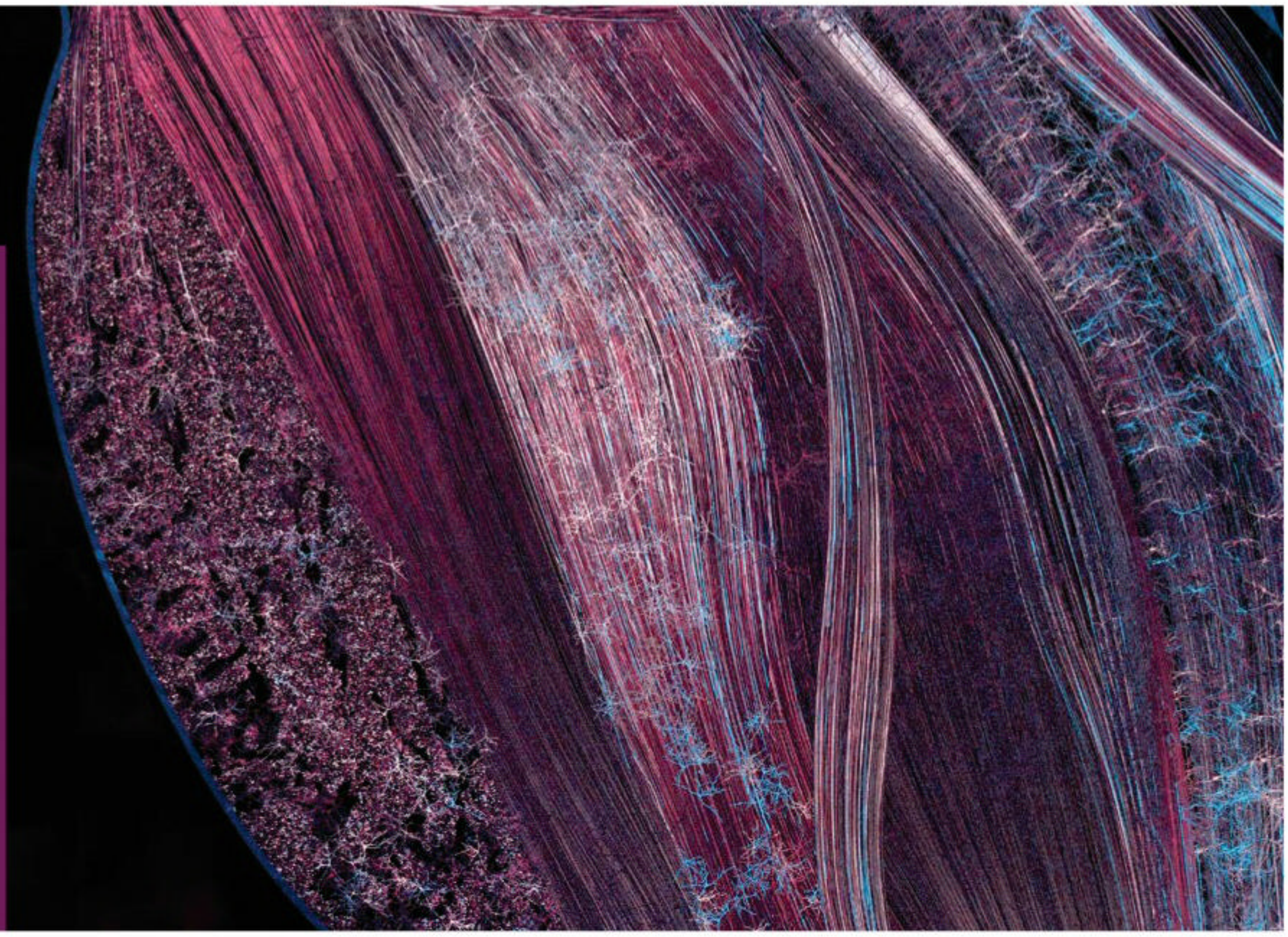
Damasio stresses the evolutionary advantage of consciousness. He maintains that it evolved as a sophisticated means of upholding homeostasis: the self-regulating process by which biological systems maintain stability, while adjusting to conditions that are optimal for their survival. All organisms possess efficient automatic regulatory mechanisms. Damasio claims that consciousnesses permits an extension of these automatic homeostatic mechanisms, which serve the important function of allowing for flexibility and planning in complex and unpredictable environments. "For a long time in our history of life we had organisms without any nervous system," Damasio explains. "Minds came out of nervous systems as processes to help maintain life."

Damasio believes there "has been a very incorrect idea that what is important in the mind has to do with perception – particularly reasoning – and representation of the outside world."

The Accelerating Research on Consciousness Initiative is focusing much of its efforts and energy on understanding consciousness from neuronal mechanisms. The project's leading coordinator, Lucia Melloni, says that in spite of challenges, progress has been made to date. Data has been collected for a video game that aims to manipulate consciousness. Another experiment evaluates how the brain continually perceives images when a subject is conscious. "This is very important because most studies in this field so far have looked at what brings a stimulus into consciousness," she says. "But very few have looked at what allows that continuum to keep flowing."

Melloni is confident significant progress is on the horizon. "This collaborative initiative is happening under the umbrella of open-democratic science," she says. "So the data sharing aspect that will come at a later stage is something to look forward to."





The laminar structure of the cerebellum (left) is the region of the brain involved in movement and proprioception, the ability to calculate where your body is in space. The pons (right) is the largest part of the brain stem, a region involved in movement – and implicated in consciousness.

JP O'MALLEY is a freelance journalist based in London.

After death – what?

Most modern funeral practices don't do much good for the planet. **MANUELA CALLARI** takes a look at what happens, scientifically speaking, if nature is allowed to take its course after we die, and emerging options that soften our carbon footprint after our exit.

Overlooking the coastal sandstone cliffs south of Sydney's CBD, gravestones in Waverley Cemetery stand like sentinels, aligned like a military parade. A Yulan magnolia grows out of the grave of a post World War II Italian migrant, at rest since 7 May 1977. It's as if it is drawing its sustenance from the deceased.

Life depends on death – a circle that has been going on forever. Saplings grow out of rotting trees, and marine carcasses provide a bounty of nutrients for deep water organisms.

When creatures die, they decompose and become the nutrients that other life forms need to flourish. But most humans end up embalmed and buried, or cremated. Are the rituals we have created messing with this cycle of life?

Some think so. "Green death" trends have emerged in the funeral industry to respond to people's growing concerns around the ecological burden of traditional burial practices.

Waverley Cemetery in Sydney has a commanding position – but why push up daisies and weeds when human remains could be regenerating native bushland in natural burial grounds?

LEFT: KAISPHOTO / GETTY IMAGES. ABOVE: WIKIMEDIA COMMONS

The science of human decomposition

First, what happens when a body decomposes out in the open? A little warning here is due: this is not a story for the squeamish. When you die, your heart no longer pumps blood through your veins. Gravity draws the blood towards the ground, where it settles. Your lungs stop functioning, which means you're not breathing in oxygen or expelling carbon dioxide. As carbon dioxide builds up and dissolves in the pooling blood, it begins to form carbonic acid, which dissociates into bicarbonate and hydrogen ions, making the blood acidic.

Simultaneously, enzymes involved in your cells' metabolism throughout life begin to digest the cells' membrane, which, combined with a decreased blood pH, causes cells to rupture and spill out their guts. "Everything starts to break apart," says Dr Maiken Ueland, a researcher at the Centre for Forensic Science and the deputy director of the Australian Facility for Taphonomic Experimental Research (AFTER) at the University of Technology Sydney.

When your cells begin to crumble, they release nutrients that the human microbiome – all the bacteria, fungi and viruses and other microbiota living in you – love to gobble up, literally eating your body from inside out.

Your microbiome helps digest food and keeps your immune system in good shape throughout life. But when you're dead, your immune system shuts down, and all of a sudden, trillions of microorganisms have free rein.

The microbiota break down carbohydrates, proteins and lipids, producing liquids and volatile organic compounds as byproducts. These build up inside your abdomen and make you look bloated. After three days of decomposition, these compounds release, causing a distinctive "death" smell. Carbon dioxide, methane, and ammonia gasses are among the contributors. Hydrogen sulphide, also present in farts when you're alive, plays a critical role. But putrescine and cadaverine, which are formed from the breakdown of amino acids, are the biggest culprits.

Ueland, who studies forensic taphonomy – the process of corpse decomposition – says the gasses emitted from the body as it breaks down attract more fungi, bacteria, worms, insects and scavengers to the banquet. A decomposing body creates a remarkably complex ecosystem, which taphonomers call the necrobiome.

Blowflies are generally early comers. They start to lay eggs from which maggots hatch within 24 hours. One blowfly can lay about 250 eggs, so if a few hundred blowflies lay eggs, there are soon tens of thousands of hungry maggots crawling on your body, ready to contribute to the decomposition process. Larvae consume the soft tissue first, says Ueland. Then the skin falls apart, and all that is left is your skeleton, which will continue to break down for decades.

As the feast goes on, more nutrients are released into the surrounding environment. For every kilogram of dry body mass, a human body naturally decomposing will eventually release 32g of nitrogen, 10g of phosphorus, 4g of potassium, and 1g of magnesium. So an average 70kg live human body, which consists of 50–75% of dry body mass, would release roughly 1,400g of nitrogen, 434g of phosphorus, 174g of potassium and 43g of magnesium after death.

Taphonomers call this puddle of nutrients around a body "the cadaver decomposition island". Initially, some of the vegetation in this island dies off, possibly because of nitrogen toxicity. But as the nutrients are further digested by bacteria within the island they act as fertilisers, transforming the island into a vegetation oasis.

Death 1.0: the industrial age

In a typical burial, the body is embalmed and put in a coffin made of oak or elm. The wooden capsule is buried about two metres underground, possibly under a slab of concrete. Formaldehyde is often used as an embalming fluid. It bonds proteins and DNA in the cells together so tightly that the microbiome can't break it down, preventing tissue from decomposing for decades.

Even if a body isn't embalmed, the coffin in which it lies hinders the natural decomposition process, and the nutrients released are not easily accessible to the microorganisms and scavengers in the soil.

If you're not keen on burial, you can always choose to be cremated. Since the 1950s, cremation has become more popular than burial, with about 70% of Australians opting for it. But cremation, too, cuts the circle of life and death short. It transforms a body into mainly three things: ash, water vapour and a lot of carbon dioxide. Not only will cremated bodies not fertilise any vegetation oases, burning them up is far from sustainable.

According to the Department of the Environment and Energy, a modern cremator uses the equivalent of 40 litres of petrol for an average body. An older crematorium furnace can consume up to twice that amount of fuel.

Cremating a dead body releases about 50kg of carbon dioxide and a bunch of toxins into the atmosphere. And the carbon footprint doesn't end at the crematorium door.

"What about the 100 people driving to the crematorium, then driving back to Uncle Bob's house to have a barbecue?" says Kevin Hartley, founder and director of Earth Funeral. "And what about all the catering and all the energy and bits that go into it?"

Give and take: Eco-friendly after death practises that give back are the subject of many start-ups. The Capsula Mundi, above, is an Italian-designed biodegradable casket above which you can plant, and nourish, a young tree. Memory Gardens, such as this one in Le Bono, France, offer the option of depositing ashes under different trees in a headstone-free green space.

CAPSULA MUNDI

Hartley estimates that at a typical, small-size cremation and funeral, the event can release up to one tonne of carbon dioxide – the equivalent of driving a petrol car for six months. Fifty trees have to grow for one year to capture just one tonne of carbon dioxide emissions.

Death 2.0: the eco-age

An interest in pared-down, eco-friendly, end-of-life options has grown, ranging from biodegradable pods that turn a body into a tree, to mushroom burial suits that devour dead tissues.

"There's a whole suite of alternative technologies in this space," says Dr Hannah Gould, a cultural anthropologist with the DeathTech Research Team at the University of Melbourne. "But alkaline hydrolysis and natural organic reduction are the major alternatives that have legs."

Alkaline hydrolysis, also known by the catchier name of "aquamation", is the fire-free alternative to cremation. It produces less than 10% of the carbon emissions of traditional cremation, doesn't release toxins, and generates nutrient-rich water.

The body is placed in a pressure vessel filled with an alkaline water solution of potassium hydroxide or sodium hydroxide or a combination of both, with a pH of 14. The solution is stirred and heated to about 160°C at high pressure to prevent boiling.

In a few hours, the body breaks down into its chemical components. All that's left is a tea-like solution that is very good for plants, so family can take home the sediment of minerals for scattering.

"The environmental footprint of alkaline hydrolysis is much less than cremation and much, much, less than conventional burial in a graveyard," says Professor Michael Arnold, a historian and philosopher

ANDIA / GETTY IMAGES

> Aquamation is the fire-free alternative to cremation. All that's left is a tea-like solution that's good for plants.

with the DeathTech Research Team.

According to a report by the Netherlands Organisation for Applied Scientific Research (TNO), the estimated environmental cost for disposal of the dead is about $102 for a burial, $77 for cremation, and $4.15 for alkaline hydrolysis. "It's a huge factor," says Arnold.

Aquamation is legal in Australia but not widely available. There are only a handful of companies that offer the service, and, Arnold says, the practice remains little known by most. It was recently in the spotlight after the death of South African archbishop Desmond Tutu, who requested his remains be aquamated. Arnold hopes Tutu's choice will increase the practice's popularity.

The other alternative is natural organic reduction, or human composting. The body is placed into a vessel with a mix of soil, wood chips, straw and alfalfa. Microbial activity stimulates decomposition. Within about four weeks, the result is around 760 litres of humus. Family members are welcome to keep some of it; the rest is used as a fertiliser. The world's first human composting company opened its doors in Seattle, US, at the end of 2020 and has since expanded to four states, but human composting isn't yet legal in Australia.

The regulatory approval path of a new way to dispose of corpses is tedious. But appealing to the mass market remains the biggest challenge – eco-friendly body disposal is still a niche market.

"People who might want to pick these options tend to be those who are pretty concerned about the environment, who are into sustainability, alternative lifestyle, are a bit hippie," says Gould. "But there is also a growing cultural desire to return nutrients to the earth."

Arnold agrees. "A lot of people think that the body is something to be disposed of without much fuss, and cremation is appealing for that reason," he says. "A smaller group of people think of the body as a resource rather than a waste – a resource that can and should be utilised by other living beings."

In recent years, natural burial grounds have gained some popularity. Here, the body is buried without embalming in the topsoil, in a softwood or cardboard coffin or a shroud. Usually, there is no gravestone or headstone. Only about 2% of people opt for a natural burial.

Restoration burial grounds

Hartley had worked in funeral services for 15 years when someone asked what his plans were for his body after death. "Being reasonably young, I hadn't really thought about it," he says.

It was then that he began to ponder the environmental impact of the furnace he had operated for so many years, and began to question whether that was indeed what he wanted his final act to be.

Hartley began to contemplate taking natural burial to the next level. "Restoration burial grounds is the term that we favour," he says.

His not-for-profit organisation plans to convert pieces of distressed land, such as overused farmland on the edges of cities, to burial grounds that offset the cost of burial by "multiple times".

The bodies will nourish and fertilise the barren land, restoring the native Australian bush. That, in turn, will attract native wildlife and, eventually, the land will be managed like a national park.

Regular natural burial grounds might offset the carbon cost of a burial, but being carbon neutral is no longer enough, Hartley says.

"We put the Earth bank account into deficit," he says. "We are way overdrawn. We want to put back into the planet.

"Death is part of life. Everything is cyclic. We're interested in the restoration of the nexus between death and life for people and have a genuine return to the earth."

It's a plan that might revolutionise the look of Australian cemeteries – rows of gravestones giving way to Australian native forests buzzing with wildlife. ⊙

MANUELA CALLARI is based in Sydney. Her last feature, on the potential of mRNA treatments, appeared in Issue 92.

NASA’s test of a system to defend Earth from an asteroid collision is underway. There’s much at stake and much to learn, as **RICHARD A. LOVETT** explains.

DARTing towards Dimorphos

NASA / JOHNS HOPKINS / APL / STEVE GRIBBEN

In this artist's impression, NASA's Double Asteroid Redirection Test (DART) spacecraft is approaching the binary asteroid Dimorphos – which is scheduled to occur on 26 September this year. DART is designed to test whether it's possible to deflect an asteroid from its path by smashing a spacecraft into it – a potentially Earth-saving move.

In the 1998 science fiction movie *Armageddon*, Bruce Willis sacrifices his life to plant a nuclear device on an asteroid hurtling toward Earth, managing to blow it (and himself) to pieces moments before it's too late.

It's high drama, but not all that realistic – as astrophysicist Alan Duffy lamented in our last issue – because unless the nuke is big enough to vaporise the entire asteroid (not a good thing to be setting off that close to Earth, even if it was possible), all it would do would be to convert the incoming asteroid into a shotgun blast of smaller ones, all big enough to cause widespread damage.

Better, scientists say, to intercept such an asteroid far away – months, years, even decades before it has a chance to strike. "I would want to find an object at least 10 years before impact," Lindley Johnson, NASA's planetary defense officer, said a few years ago at a NASA briefing.

That way, all that's needed is to give the asteroid the tiniest of nudges to change its orbit from apocalyptic to nothing of concern. And how best to nudge it? The best option, many think, is to hit it with a "kinetic impactor" – not a bomb, but a small, fast-moving object with sufficient momentum to shift its orbit enough to do the trick, but not so hard that it splits the asteroid into multiple pieces.

"If you give too hard a push, instead of moving it out of the way, you might have five objects to keep track of instead of one," says Andy Rivkin, a planetary astronomer at Johns Hopkins University's Applied Physics Lab (APL), in Maryland, US.

If that, too, sounds like science fiction, think again. Rivkin leads a team on a NASA mission designed to test this approach with a 160-metre asteroid called Dimorphos. Named DART (Double Asteroid Redirection Test), the mission launched on 24 November 2021, and is expected to strike on 26 September 2022. Not that Dimorphos poses any risk to Earth. The goal is simply to test two things. First, can we actually hit such a small, distant object with a fast-moving spacecraft.

"It's the smallest natural object we've ever tried to land on," Rivkin says. Though "land" is a bit of a euphemism. DART will be coming in fast, and isn't exactly going to make a gentle landing. Crashing hard is the whole point, in fact. But it's still a daring navigational feat: hitting an object about the size of a soccer stadium 11 million kilometres away with a spacecraft moving at 6.6 kilometres per second (24,000km/h) at the time of impact.

The other goal is to see how Dimorphos responds to the impact, because hitting an asteroid with a spacecraft isn't like hitting a billiard ball with the cue ball. "When we have a high-speed impact on an asteroid, you create a crater," explained Andrew Cheng, another member of the DART team, at that NASA briefing. "You blow pieces back in the direction you came from."

That, he says, means that even though the spacecraft will hit with the energy of about 2,000 tonnes of TNT, the backward-blowing debris will also help change the target's trajectory. "The amount can be quite large," he says. "More than a factor of two."

The SpaceX Falcon 9 rocket (above and opposite top left) carrying the DART and LICIACube launched last November, but mission planning and testing has occupied years. DART's rollout solar array was tested (opposite right) on the International Space Station in 2017. It was shipped from the US east coast to its California launch site in a specialised shipping container (opposite bottom) the month before launch.

ABOVE: NASA / JOHNS HOPKINS APL / ED WHITMAN

FRAMING THE TEST

The kinetic impactor idea isn't new. The problem always was that it was hard to test, because the desired nudge is in the order of millimetres or centimetres per second – somewhere between the pace of a caterpillar exploring a leaf and a three-toed sloth in high gear. Given the fact that asteroids are generally

FROM TOP: BILL INGALLS, JACK FISCHER, ED WHITMAN / /NASA / JOHNS HOPKINS APL.

It's a daring feat: hitting an object the size of a soccer field 11 million kilometres away with a spacecraft moving at 24,000km/h at the time of impact.

orbiting the Sun at somewhere around 30km/s, that makes it very difficult to measure.

The genius of DART was the realisation that some asteroids are binary pairs, in which a small body circles a larger one. These orbital movements aren't fast – in the case of Dimorphos, in the order of 10-20cm/s. That means the effect of a kinetic impactor on the small one can be easily measured simply by looking for the change in its orbit around its larger companion.

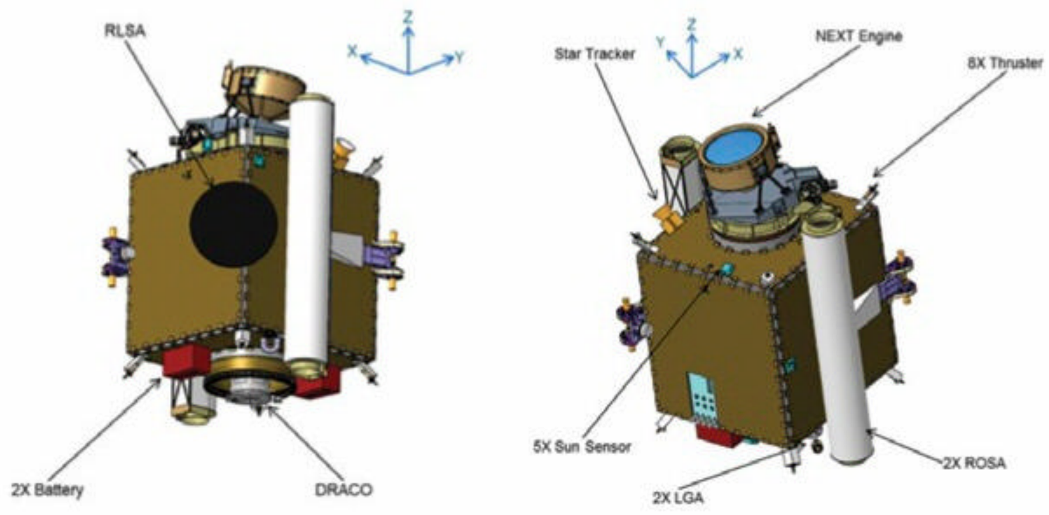
"Say, before the impact, [the orbit] takes 11 hours and 55 minutes," Rivkin says, "and now it's 11 hours and 47 minutes. You can say the change is due to what we did." As an added benefit, there's no chance the impact could knock it out of orbit, accidentally turning a non-threatening asteroid into one that might someday wind up on a collision course with Earth.

It is, of course, not quite that easy.

The only way to measure a change in the orbital speed of a moonlet like Dimorphos using telescopes on Earth is if it circles its primary in the same plane

WHAT'S IN THE BOX?

DART packs a lot of tech into its compact cube.



- **RLSA** Radial Line Slot Array antenna; the primary communication link with Earth; assisted by two low gain antennas (**LGA**).
- **DRACO** Didymos Reconnaissance and Asteroid Camera for Optical. "Traditional navigation techniques would only get DART somewhere within about 9 miles of the target asteroid," said APL's Zach Fletcher, DRACO lead engineer. "To achieve our mission objectives, we need to remove the rest of that error via on-board optical navigation." Assisted by **five sun sensors** and a **star tracker**.
- **ROSA** Two Roll Out Solar Arrays – 8.6m x 2.3m – produce 6.6 kilowatts of power, stored in **two batteries**.
- **NEXT Engine** NASA Evolutionary Xenon Thruster; a solar electric propulsion system, in which power from the ROSA array is harnessed to accelerate xenon propellant to speeds up to 145,000km/h (40km/s).
- **Thrusters** Eight thrusters (on each corner) help with course correction.

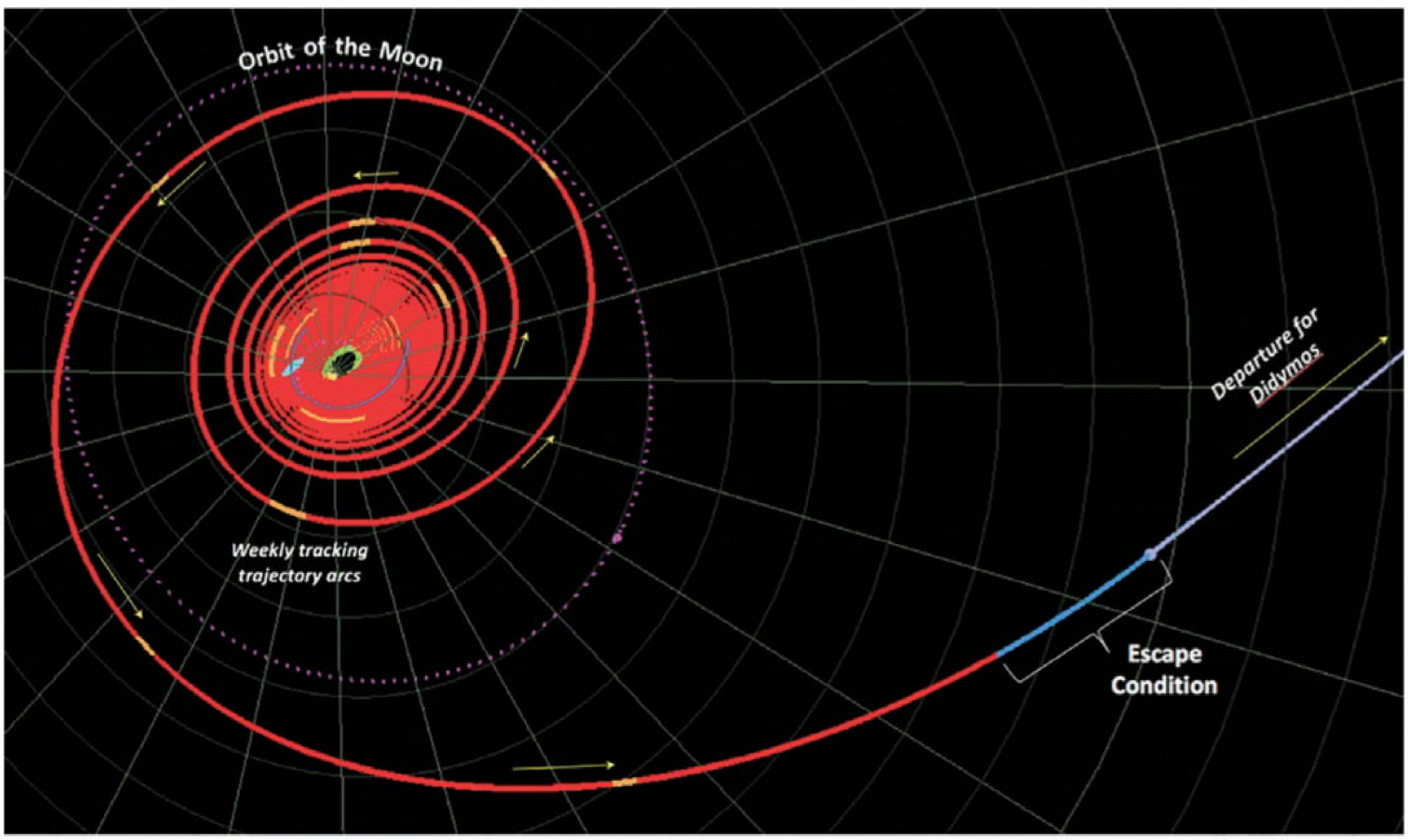
as the Earth. That makes it an "eclipsing binary" – meaning that every orbit it alternately passes in front of and behind its primary. That produces a "light curve" in which the combined brightness of the two objects periodically dips, as each obscures part or all of the other. Carefully timing these dips allows the change in the orbital period to be easily measured.

In addition to having its orbit perfectly aligned for it to be an eclipsing binary, the asteroid pair needs to be close enough to Earth for astronomers to easily see its light curve, and small enough for the impact to produce a measurable change in its orbit.

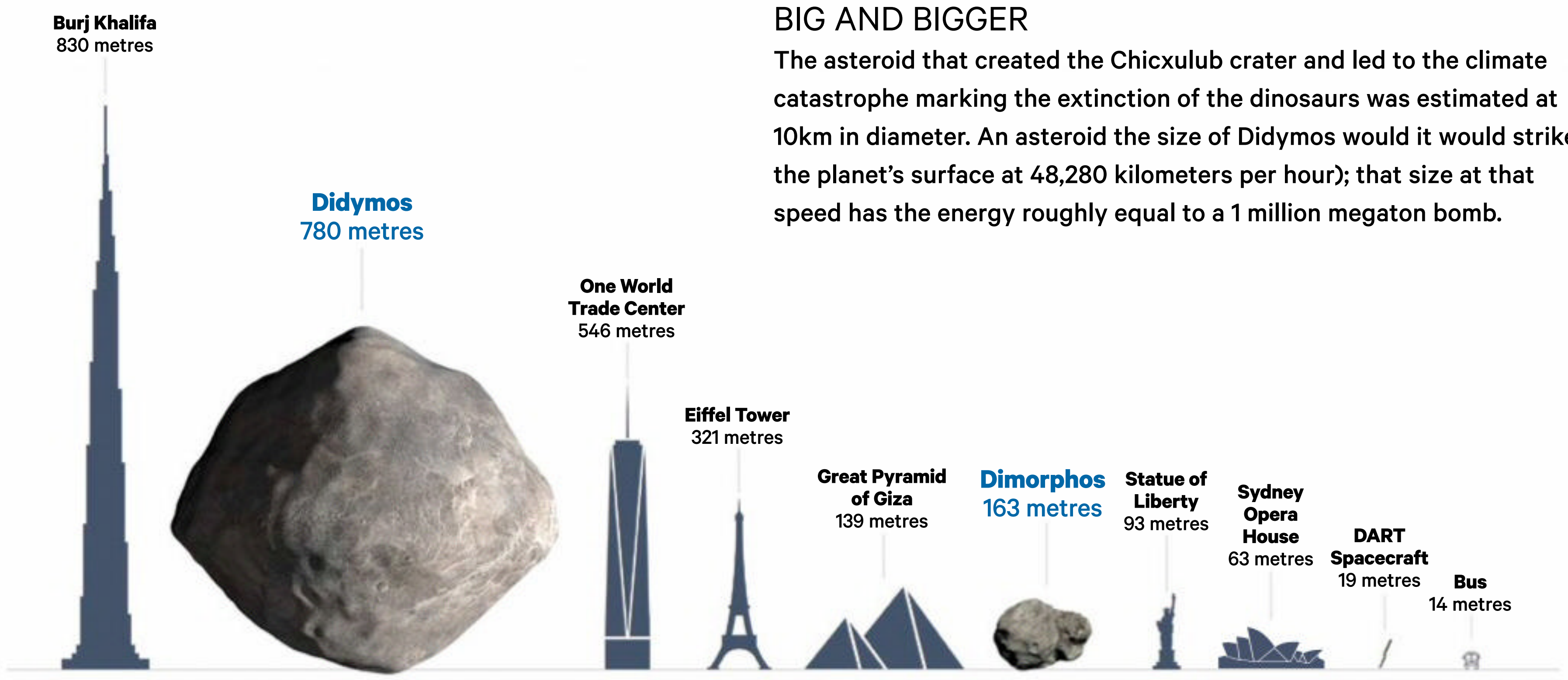
With all of those requirements, Rivkin says, the options become very limited, with Dimorphos not only being by far the best choice, "but the only choice if we wanted to do this in the next 20 to 25 years."

AFTER IMPACT, INVESTIGATION

Although DART's primary goal is to test a means of what NASA calls "planetary defense", it also has scientific objectives. Scientists now know that about 16% to 20% of all near-Earth asteroids are in binary pairs, but other than an incidental discovery by NASA's Galileo mission – when, en route to Jupiter in 1993, it passed 2,400km above Ida, a 56km-long potato-shaped asteroid, and spotted a previously unknown 1,400m moonlet – scientists have never had a chance to see an asteroid moon up close and personal. That said, DART won't give them very long to look at it. Dimorphos is so small that it will only be a single pixel in the spacecraft's camera until

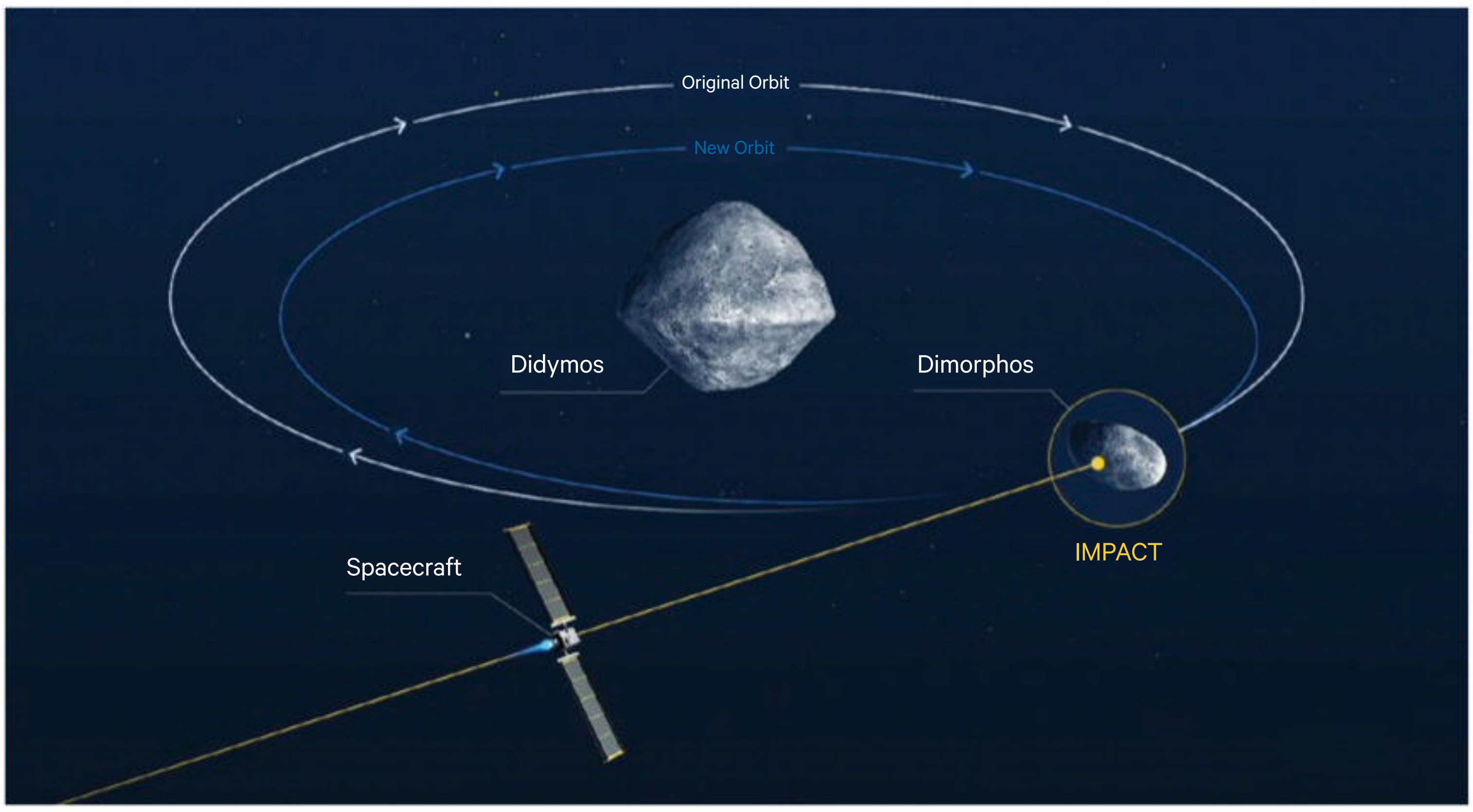


FROM TOP: NASA



BIG AND BIGGER

The asteroid that created the Chicxulub crater and led to the climate catastrophe marking the extinction of the dinosaurs was estimated at 10km in diameter. An asteroid the size of Didymos would it would strike the planet's surface at 48,280 kilometers per hour); that size at that speed has the energy roughly equal to a 1 million megaton bomb.



DART will use NASA's low-thrust NEXT-C ion propulsion system to escape Earth orbit (opposite) and reach Didymos. On final approach (above), DART's navigation will be a combination of instruction from Earth and onboard optical instruments to guide it to the impact point. LICIACube will separate 10 days from the destination, alter course and fly past Didymos at 55km distance just 165 seconds after impact.

BOTTOM: EUROPEAN SPACE AGENCY

the last hour or so before impact. Then, it will rapidly expand.

"Most of the good images that will let us look at its surface will be coming in the last two minutes," Rivkin says. "It's going to be a long ride, and a lot of payoff in the last bit."

The spacecraft's camera is descended from the one that sent back stunning images from Pluto during the New Horizons flyby in 2015. And because Dimorphos is a lot closer to Earth, the expectation is that DART will be able to return megapixel images, right up until the moment of impact, possibly as quickly as one frame per second.

One of the things this will reveal is what Dimorphos looks like. Is it a rubble pile, like many larger asteroids tend to be, or is it a single, solid block? That will tell a lot about how it may have been formed.

If it is a rubble pile, it may have formed from

THE GRAVITY TRACTOR

DART is based on the idea that the best way to shift an asteroid's course is to push it. But it's also possible to pull it using nature's own science-fiction-style tractor beam: gravity.

Gravity works both ways. If you are near an asteroid, its gravity tugs on you. But yours also tugs on it. Thus, if you want to change the course of an asteroid, all you need to do is to hover above it for an extended period of time, waiting while gravity tugs it your direction. If needed, the effect can be strengthened by first plucking a boulder from the surface of the asteroid, thereby adding its mass to that of the hovering spacecraft.

The effect is small, but it adds up, and a few years ago NASA had a mission in development called ARM (Asteroid Redirect Mission) that would actually have tested it out. (The mission was shelved by the Trump administration in 2017.)

The gravity tractor's main advantage is that it's gentle. There's no risk of breaking the asteroid into scattered pieces, any one of which might become a new hazard. Its disadvantage is that it is complex, slow, and needs a new type of rocket nozzle not yet created – one that wouldn't undo the process by blasting its exhaust right at the asteroid the spacecraft is trying to tow, thereby shoving it away rather than pulling it forward.

material flung off by Didymos, itself suspected to have once been a fairly rapidly spinning rubble mass early in its history. This material may then have coalesced into a new, smaller rubble pile…

But that's not the only possibility. It could be that Dimorphos will prove to be a single giant boulder flung out from Didymos as a shard from an ancient impact, says Maurizio Pajola, a planetary scientist at the National Institute for Astrophysics in Italy. On asteroid Ryugu, from which Japan's Hayabusa2 mission recently returned a sample, the researchers were startled to find a single, giant boulder, about 150m long, sitting atop the asteroid.

Ryugu isn't much bigger than Dimorphos' primary, Didymos. Could Dimorphos be a similar-sized rock that somehow escaped into orbit? Part of the answer will come from the final images returned by DART's camera, but more will come from a 14kg CubeSat hitching a ride with DART itself. Called LICIACube (Light Italian CubeSat for Imaging of Asteroids), it was built by the Italian Space Agency and will detach from DART 10 days before impact. It will then use tiny thrusters to slow down slightly and move itself off course, so that it will fly by Dimorphos 165 seconds after impact, at a distance of 55km.

But that's just the beginning. The European Space Agency is planning a mission called Hera, which will arrive at Didymos and Dimorphos in 2026, brake into orbit, and conduct a "crime scene investigation" of the DART impact. "Most of the science will come from the Hera mission," says an asteroid scientist who didn't have press clearance to speak officially about the project.

NUCLEAR OPTION

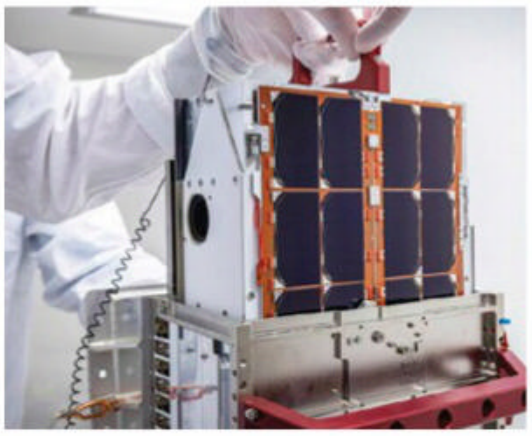
If gentler measures fail, nukes are still an option for warding off an incoming asteroid. But not in the blow-it-up manner depicted in the 1998 movie *Armageddon*. Instead, a bomb (or bombs) could be detonated close to the asteroid, and energy from the blast would superheat the near side of its surface, vaporising it and causing material to blow off into space. The effect would be to turn that side of the asteroid into a rocket nozzle powerful enough to divert its course.

This might be the best response if the Earth finds itself threatened by a fast-moving, incoming comet, like the one in the 2021 movie *Don't Look Up*, where there's not a lot of time to react. But for the type of near-Earth asteroid most likely to be dangerous, like the 800m object that passed by the Earth on 18 January (about the size of the Empire State Building), it's probably not necessary to resort to nukes – given that they'd be, at the least, highly controversial.

What it will find is, of course, an open question. But one interesting factor will be comparing LICIA-Cube's images of the crater formed by DART's crash to those seen by Hera, four years later. That's because the surface gravity on Dimorphos is probably no more than one-millionth that on Earth. This means that events on Dimorphos occur in super-slow motion – so slow that it could take several minutes for the crater formed by DART to assume its final shape.

Comparing the crater seen by LICIACube 165 seconds after impact to that seen by Hera long after things have had time to settle into their final shape could shed important light on cratering processes on low-gravity worlds throughout the Solar System. But there are, of course, other things to learn. Images from DART, LICIACube and Hera, for example, will let scientists tabulate statistics on the sizes of boulders on Dimorphos' surface. Doing this is really

DART (left and bottom) was mostly assembled by a mechanical engineering team from Johns Hopkins University Applied Physics Laboratory. The LICIAcube (below) was built by the Italian Space Agency. The end game is to have the knowledge and technical ability to avoid a catastrophic asteroid impact on Earth (illustration, opposite).



NASA / JOHNS HOPKINS APL / ED WHITMAN X3

The biggest impact in recorded history was in 1908, when a 50–60m long asteroid exploded over Siberia, levelling trees over a 2,100 square kilometre region.

WHAT HAPPENS IF WE GET HIT?

The most spectacular asteroid impact in recent memory was in 2013, when a 20m space boulder exploded above Chelyabinsk, Russia, blowing out windows and injuring nearly 1,500 people, mostly with flying glass.

But the biggest in recorded history was in June 1908, when a 50-60m long asteroid exploded over the remote Podkamennaya Tunguska River region in central Siberia, more than 3,000km north-east of Moscow. Known as the Tunguska event, the blast levelled trees over a 2,100 square kilometre region and produced a shock wave heard as far away as London, England.

If anyone died there, nobody knows. It was too remote, and too long ago, for anyone to know. But if a similar blast occurred over a modern, major city? The death toll would be in the millions.

In 2019 at a Planetary Defense Conference in the US, the International Academy of Astronautics war-gamed just such a scenario. In it, the Earth was threatened by an asteroid about the size of Dimorphos: not a dino-killer, but big enough to do a lot of damage.

In the scenario (conducted while DART was still in its planning stages), efforts to divert it with a kinetic impactor struck it too hard and broke it into two pieces – one of which wound up still on course for Earth, eventually striking a major city with the force of a 15-megaton bomb.

It was, of course, a worst-case scenario. But there's no value in war-gaming one in which the asteroid either misses or is easily deflected, says Paul Chodas, of NASA's Centre for Near-Earth Object Studies. "We learn by studying these what-ifs," he says.

Not to mention by testing our defence technologies, as is being done with DART.

tedious, but it will be another important clue as to how double asteroids like Didymos and Dimorphos form.

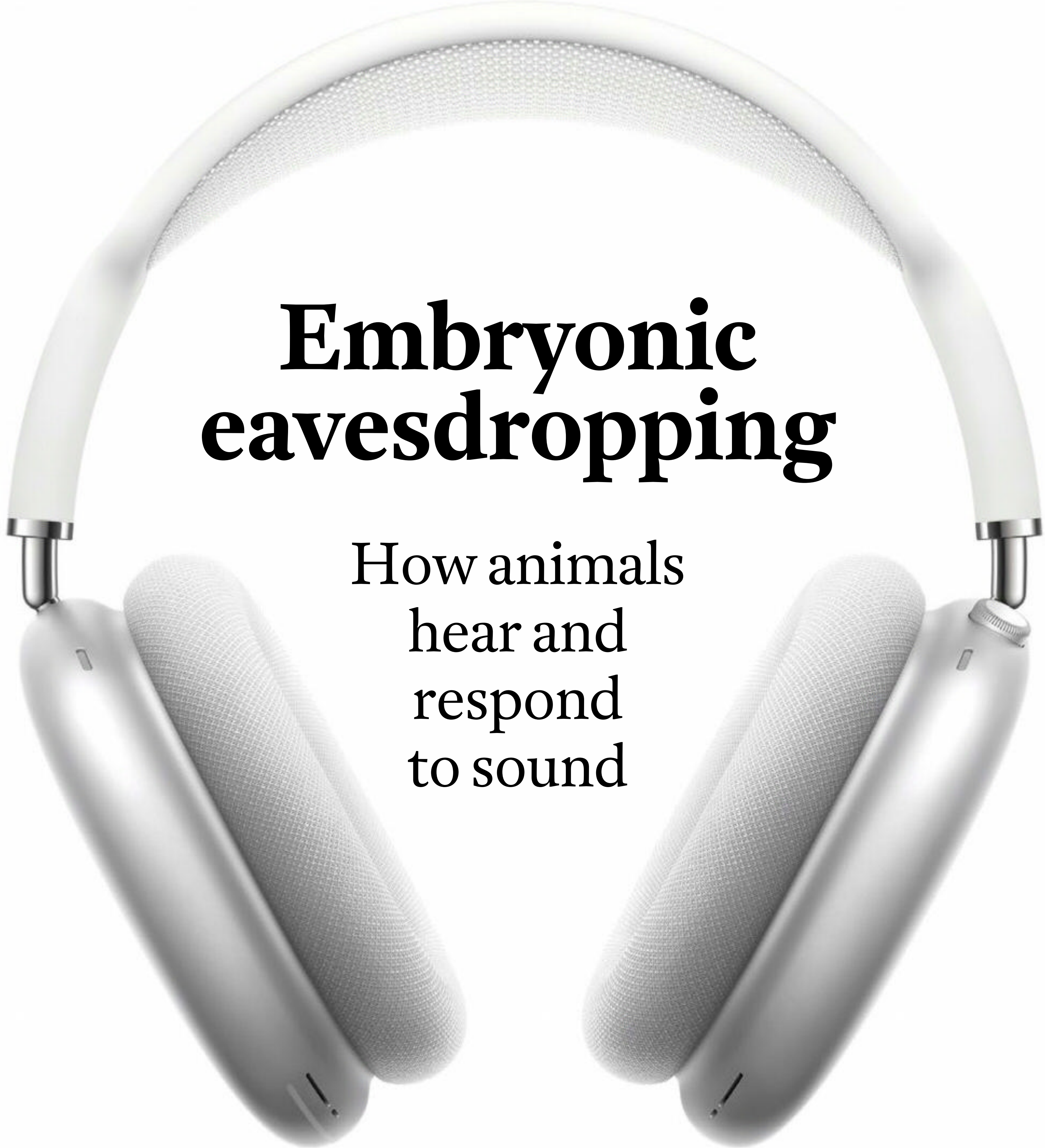
Also important is looking for landslides that might indicate how tidal forces from Didymos are changing the landscape on Dimorphos. Along with that, scientists will be looking for cracks in Dimorphos' rocks, trying to see how solar heating and night-time cooling might be making them break down and split, much as temperature changes on Earth cause cliffs to break and drop rocks into valleys far below.

That said, DART's primary purpose is, and will remain, planetary defence, so we can learn more about how to avoid being clobbered by an asteroid in the near or distant future.

"This is a hazard that the dinosaurs succumbed to 65 million years ago," said John Holdren, science advisor to US President Barack Obama from 2009 to 2017. "We have to be smarter than the dinosaurs."

RICHARD A. LOVETT is a science and science fiction writer. His story about life as a principal investigator at NASA appeared last issue.

ANDREUS / GETTY IMAGES

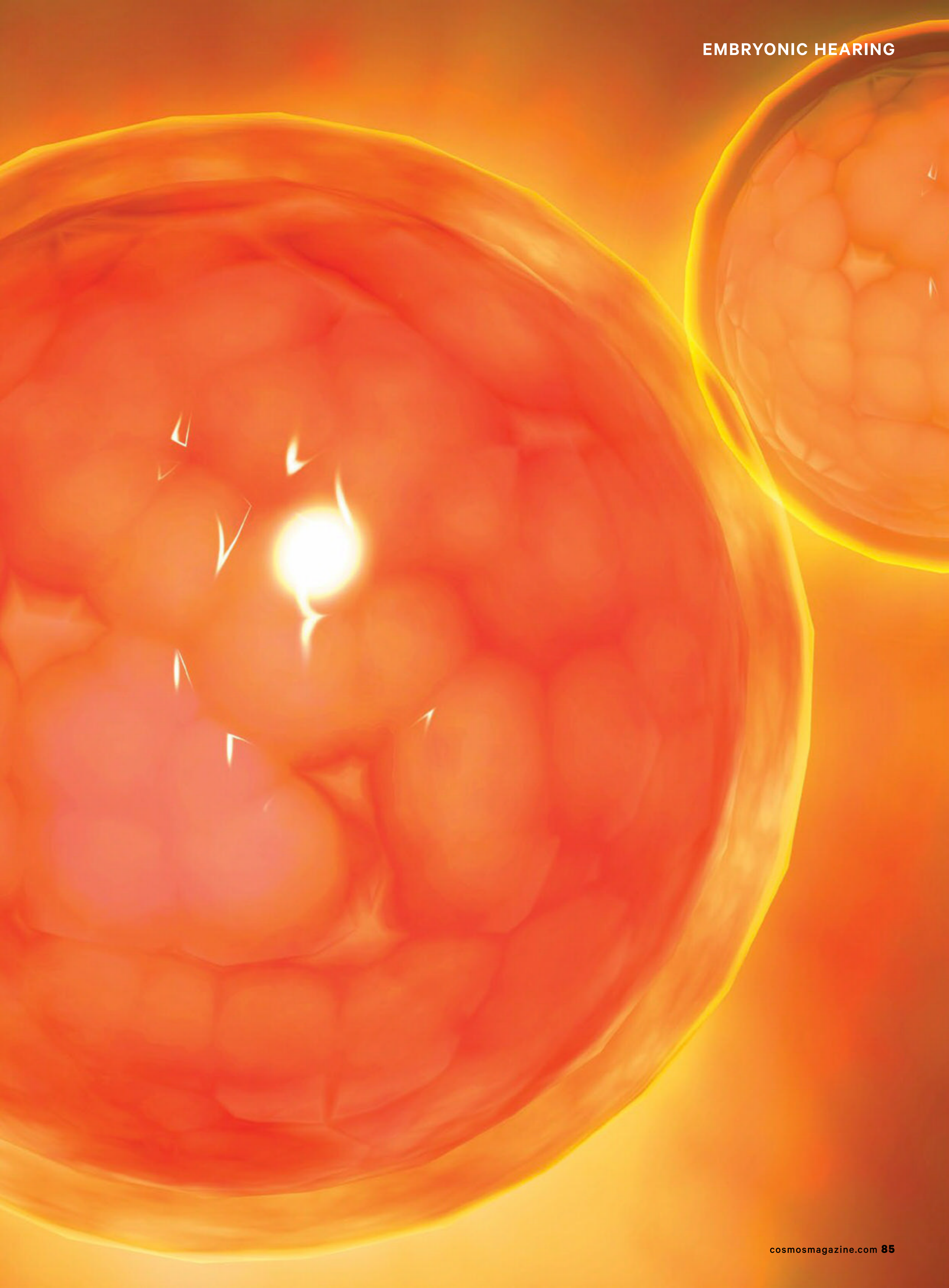


Embryonic eavesdropping

How animals hear and respond to sound

Recent findings buck the idea that embryos are passive agents, and instead suggest that by tuning into vibrations, organisms can better prepare to enter the outside world. **AMANDA HEIDT** reports.

FROM LEFT: APPLE. STOCKTREK IMAGES / GETTY IMAGES.



Birds have a rich vocal repertoire that they use to communicate with their peers, but behavioural ecologist Mylene Mariette is more interested in the calls they make when they are seemingly alone.

While working as a researcher at Deakin University, in Victoria, Mariette planted microphones in the nests of captive zebra finches (*Taeniopygia guttata*) to study how male-female pairs coordinate their parenting efforts. One day in 2014, she noticed that "sometimes one parent would produce a very different call when it was incubating by itself", Mariette recalls, which led her to wonder "whether it was communicating with the embryos, because they were the only audience there."

The cry she overheard – a form of vocal panting – is one that finches produce when temperatures rise, and while further observations showed that they do sometimes produce this heat call when alone or around other adults, it is most often made in the presence of eggs, especially those nearly ready to hatch. And the developing chicks respond: playback experiments revealed that chicks that heard the call before hatching grew more slowly, possibly to reduce the oxidative stress caused by high temperatures or to maximise heat dissipation from their smaller bodies.

> Rather than lying dormant in the safety of the egg or womb, embryos are constantly tuning into auditory stimuli that influence their developmental trajectory.

In addition, birds exposed to this heat call sought hotter nests as adults, produced more fledglings during their first breeding season, and were more amenable to trying new foods than were controls who didn't hear the heat call as embryos but were otherwise reared in the same hot conditions. Male finches, in particular, learned a more diverse repertoire of calls, which increased their reproductive success.

Mariette is not sure whether the avian parents were making the call intentionally to communicate with their young or if the chicks were eavesdropping, and she notes that it's common for an existing behaviour, such as vocal panting (which dissipates heat), to be co-opted for another purpose such as communication. Regardless of how it evolved, the exchange of information likely benefits everyone, she says.

Her group found that chicks that were exposed to heat calls as embryos begged less, though more intensely, than control chicks when reared in hot nests, perhaps because begging is energetically expensive. "If they match their parents' capabilities, they don't waste their own effort, begging more than the parents can afford," Mariette says.

Mariette and her colleagues termed the phenomenon of embryos perceiving and responding to external sounds or other vibrations "acoustic developmental programming," and they've since described it in several papers, including a recent review in *Trends in Ecology and Evolution*. When Mariette began searching for other examples, she found them across other egg-laying species – in birds, reptiles, amphibians and insects. They later found evidence in humans as well. While the researchers in those studies hadn't always set out to discover prenatal communication, their results support the idea that rather than lying dormant in the safety of the egg or womb, embryos are constantly tuning in to auditory stimuli that influence their developmental trajectory when they emerge.

These stimuli come in the form of calls, other sounds, and physical vibrations. The information can originate from parents, siblings or potential predators. Researchers are now uncovering the specific mechanisms behind the resulting developmental shifts in egg-bound embryos, as well as the potential benefits, while studies of rodents and humans are elucidating how sound influences brain development and even language acquisition in mammalian embryos gestating in a womb. (See "How sound affects development in gestating mammals", page 40.)

SOME LIKE IT HOT

Zebra finches (*Taeniopygia guttata*) which share parenting in male-female pairs sometimes make a unique call – a form of vocal panting – when incubating a nest alone in high temperatures.

Research has shown that hearing the call prompts developmental and behavioural changes in the offspring – once hatched, the young chicks beg less often and more intensely, but also grow relatively slowly, perhaps as a means of reducing oxidative damage or facilitating heat loss, the scientists suggest.

As adults, heat-exposed birds also seek hotter nests themselves and produce more fledglings during their first breeding season, suggesting that they are better adapted to hotter environments.

TAMBAKO THE JAGUAR / GETTY IMAGES

HOW SOUND AFFECTS DEVELOPMENT IN HUMANS

At 25 weeks of gestation, human foetuses can begin to respond to auditory stimuli, meaning that most foetuses can hear well before they are born during a period of critical brain development when neural connections are first laid down. Indeed, babies are born able to recognise their mother's voices, and exposure to ambient sound in utero has been linked to healthy brain development.

But while it's more straightforward to study species that lay eggs – which can be moved, manipulated, and measured relatively easily – it's harder to determine how sound affects babies in the womb.

One approach is to study infants who are born prematurely. Although an incubator in the neonatal intensive care unit (NICU) is vastly different from a womb, researchers can measure how babies respond to their environments while they are still within their 40 weeks of development.

Amir Lahav, formerly a paediatric neuroscientist at Harvard Medical School, US, came to this realisation in 2007, when his then-wife gave birth to twins prematurely at 25 weeks. "I went to the NICU as a parent for the first time, and I was shocked by the amount of noise, by the alarms and monitors and wires and trash cans," he

recalls. He approached the head of neonatal care and suggested an unofficial study – Lahav wanted to record his wife's voice, transform the audio to mimic how it might sound in utero, and play it to his twins. While the results were preliminary and did not include controls, "the medical team was amazed how my kids skipped every possible complication they would anticipate for babies born that early", including breathing problems, sepsis, brain haemorrhaging, and death.

Based on that outcome, Lahav and his colleagues designed another experiment, this time with 40 premature infants. Four times a day for a month, newborns heard either muffled, "wombified" recordings of their mothers' voices and heartbeats, or the ambient sound of a bustling NICU. Afterward, the team imaged the infants' brains using cranial ultrasonography during a routine health check. Compared with the controls, the babies who heard maternal sounds had significantly larger auditory cortexes, an area of the brain involved in hearing and language development. The results "show the benefits of maternal sounds on the brain, at least structurally", says Lahav.

Geneva University developmental neuroscientist Petra Hüppi is investigating how sounds early in development affect the infant brain – specifically, she's looking at connections between regions such as the amygdala, hippocampus, and orbito-frontal cortex. To do so, she uses music, which activates multiple regions involved with auditory, sensory and emotional processing. "Music has a particular effect on humans that is distinct from the response to language and voices," she says. "It's still not fully understood what it is."

In 2020, Hüppi partnered with award-winning composer Andreas Vollenweider to create music for babies, as chosen by babies. Vollenweider brought a veritable orchestra into the NICU and played each instrument for the infants when they were waking up, falling asleep, or active in their incubators. Based on visual observations and measurements of the babies' heart rates and eye movements, the team created soundscapes of what the infants liked best – primarily harp, snake flute and bells.

Hüppi and her collaborators then split a cohort of 30 premature NICU infants into two groups, half of whom heard the soundscapes five times a week and half of whom received the usual standard of care, and used magnetic resonance imaging (MRI) to compare their brain development to 15 full-term babies. At the end of the experiment, the brains of NICU babies who heard the music more closely matched those of babies born at full term than did the brains of the premature controls: the music-exposed babies' white matter was more fully developed, their amygdalas were larger, and the connections between regions in the brain that process acoustic and emotional stimuli were stronger.

The NICU environment, both Lahav and Hüppi agree, warrants further study. Sound could partly explain why children born prematurely have a higher incidence of behavioural or attention-related issues such as ADHD, autism, aggression, or anxiety. For NICU babies who spend weeks in an incubator, "the primary stimulation is noise," Lahav says. As a result, he adds, "the brain learns that noise is the most important thing in life," possibly making it harder to tune out background noise and focus on the task at hand.

LEFT: DON FARRALL / GETTY IMAGES

"The ability of embryos to sense sound and vibration could be ancestral, but the way it's used evolves in each species independently depending on its advantages," Mariette, now at the Doñana Biological Station in Spain, says. "When we put it all together, we realised it's very common."

Preparing for life on the outside

In some of the simplest examples of acoustic developmental programming, embryos can use sound to synchronise their hatching. Turtles and crocodiles, which bury their eggs in sandy nests below ground, do this to overwhelm predators. The reptilian embryos will call to one another and, when the chorus reaches a crescendo, begin their mad dash to escape their eggs, ascend to the sand's surface, and scurry into the water.

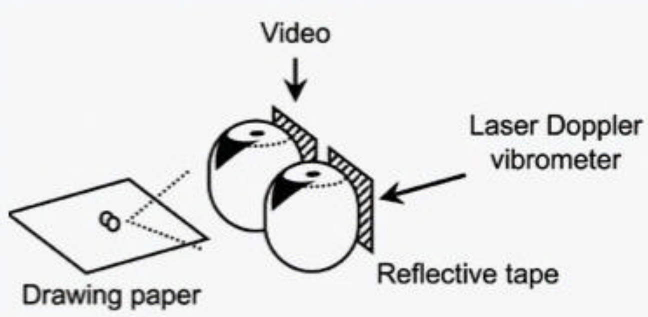
> When a signal, likely a vibration, deviates from the norm, it puts the unhatched frog embryos on alert, and signs of danger trigger an adjustment in hatching time.

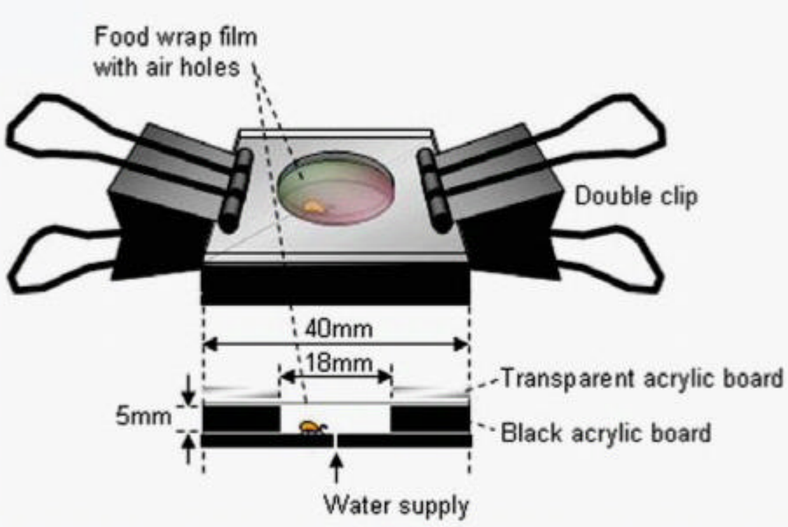
Embryos of the stink bug *Halyomorpha halys* also listen to their peers, but in their case, that's because they themselves are the predators. Hatching produces an explosive crack, which prompts all the young to emerge at the same time, so that the last ones out aren't eaten by their older kin. And clutches of the burrower bug *Adomerus rotundus* and the shield bug *Parastrachia japonensis* each hatch in unison in response to maternal vibrations in part to guard against sibling cannibalism. In the case of the shield bug, all larvae emerge at the same time to limit immediate cannibalism, while in the burrower bug, the highest risk isn't immediately after hatching but following the first moult, when older nymphs are soft and more vulnerable to being attacked by younger, smaller siblings. Simultaneous hatching can also help *P. japonensis* mothers protect and feed their young more efficiently because the larvae are at the same developmental stage.

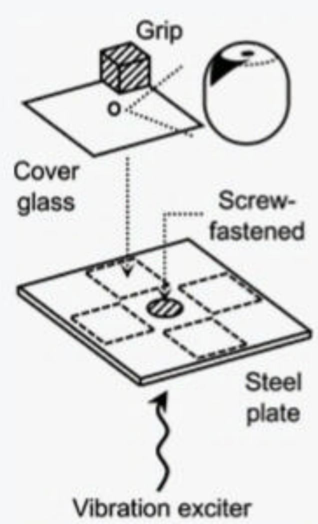
Animal embryos can also use sound to respond to the variable risk of predation by other species. Mites, for example, delay hatching by hours when they sense the vibrations of various species of predatory mites walking by or attacking, Kyoto University entomologist Shuichi Yano and colleagues found, as they are safer inside their tough eggs than as vulnerable larvae. Vibration "provides a direct channel for information transmission from the environment," Yano observes.

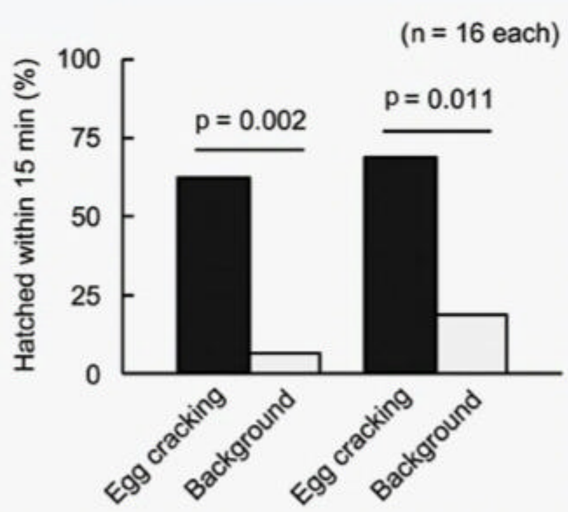
BEHIND THE SCENES

With any scientific question comes the need for a method to test the hypothesis – and the solution's not often something you can buy off a shelf. Below, to find out if mite embryos delayed hatching in response to egg predation attempts, Kyoto University researchers created a rig that made excellent use of commonly-available materials, including bulldog clips. Right and below, scientists seeking to discover the source and order of synchronised hatching in the stink bug built a nifty combination of vibration mechanisms to prove their theories.



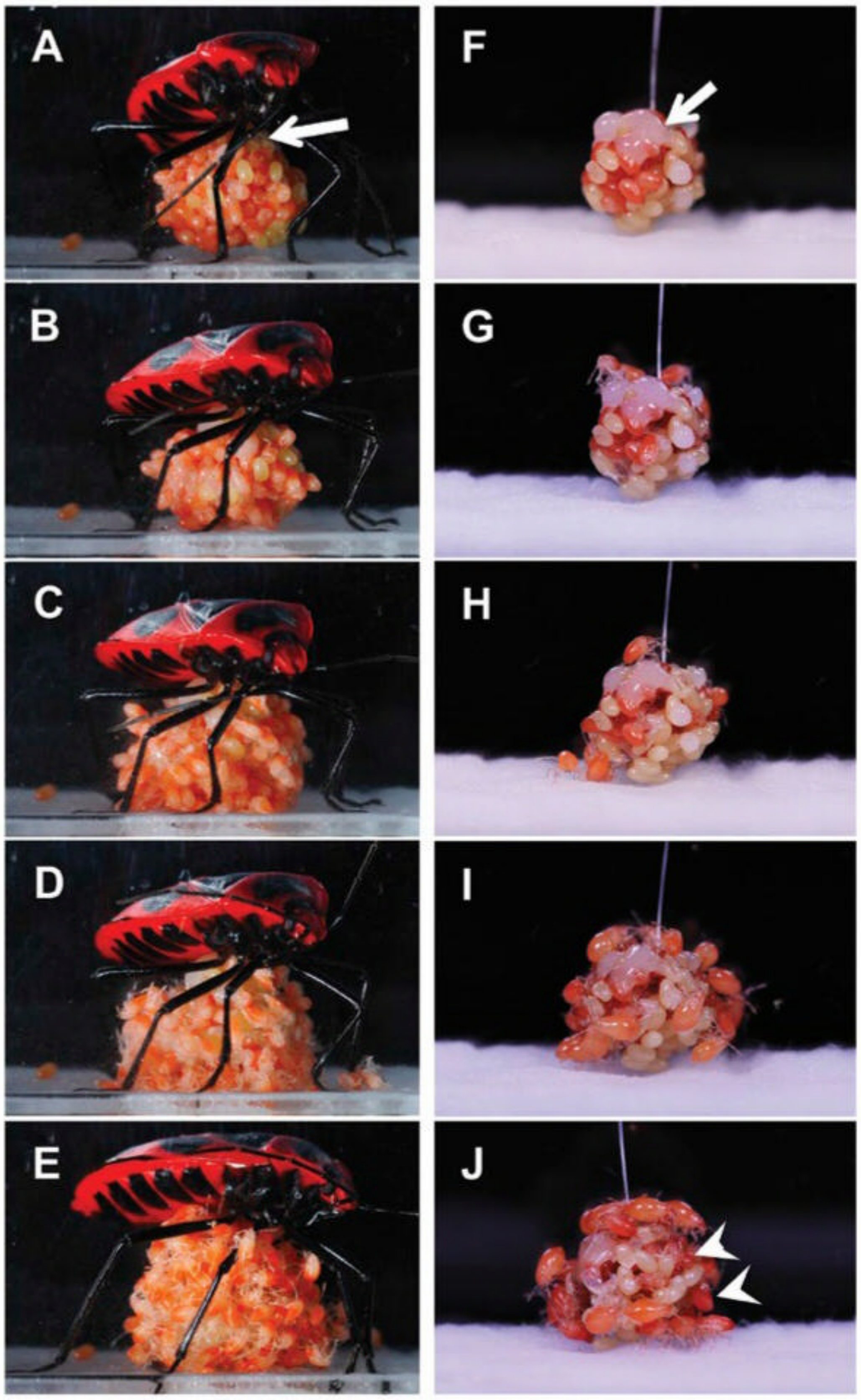






GOOD VIBRATIONS

Evidence of acoustic developmental programming in the insect world



To initiate synchronous hatching, a burrower bug (*Adomerus rotundus*) mother stands over the egg mass and begins to vibrate. When researchers allowed egg masses to hatch asynchronously without vibration, younger nymphs cannibalised their older siblings just after their first moult.

Glass frogs (family *Centrolenidae*), which lay their eggs in clusters on the undersides of leaves overhanging ponds in the neotropical rainforests of Panama, take it one step further. They are able to delay hatching if they sense a nearby predator – doubling or even tripling their embryonic period from roughly seven to up to 21 days – or they can hatch spontaneously in the face of an attack as an attempt to escape, even before they are fully developed.

This hatching plasticity comes in handy, says organismal biologist Jesse Delia, as everything, it seems, wants to eat these frogs. During his doctoral research at Boston University, in the US, he documented predation attempts on five frog species by snakes, spiders, grasshoppers and ants.

Embryos seem to be able to differentiate friend from foe, says Delia, now a postdoc at the American Museum of Natural History, but he's not sure exactly how. "There's clearly some ability to distinguish between parents and dangerous cues," he says, adding that perhaps the unhatched frogs become habituated to the sounds of their father as he mates, confronts predators, and tends the eggs. When a signal, likely a vibration, deviates from the norm, it puts the embryos on alert, Delia speculates, and signs of danger trigger an adjustment in hatching time.

Such adjustments can come with a tradeoff, however. In Delia's research, tadpoles that hatched early were less efficient swimmers and were prone to being picked off by predatory fish. In 2014, Fabien Aubret, an evolutionary biologist at the French National Centre for Scientific Research, found evidence of a similar tradeoff among newly hatched viperine water snakes (*Natrix maura*), which often emerge from their eggs synchronously with other clutches of varying ages laid in the same hollow log or other cavity.

LET IT SLIDE

Male glass frogs (family *Centrolenidae*) care for their young by keeping the eggs moist and warding off predators.

Somehow embryos are able to distinguish between predators and their parents. Researchers suspect the cue is vibrational.

When a predator attacks the clutch of eggs, tadpoles can hatch early, spilling into the water below.

The tradeoff, researchers say, is that underdeveloped tadpoles swim less efficiently and must wait for their guts to fully form before they can begin feeding.

FROM TOP: CROPWATCH, PLOS ONE

JUAN CARLOS VINDAS / GETTY IMAGES

Using infrared technology borrowed from the poultry industry, Aubret monitored the heart rate of 77 eggs he'd reared in artificial clutches of two sets of eggs that differed in age by six days. He found that the snakes can sense the heartbeats of their neighbours and shift their own accordingly: younger snake embryos had faster heart rates than controls raised in isolation, which in turn increased their metabolism.

Additionally, Aubret says, the younger snakes forewent sleep, when metabolic rates typically drop, speeding their maturation so they could hatch with the older eggs. Once they hatched, however, the younger snakes were shorter and swam less efficiently than controls.

While Aubret has since moved on to studying different species and pursuing other questions, the release of more research on prenatal communication has made him consider returning to the snakes.

For now, he says, he's excited to see what other examples researchers turn up and what they learn about how and why embryos are responding to external cues.

"I've always thought the incubation period within any egg-laying organism is a black box," he says. "We know a lot about what happens before the eggs are laid and when they hatch, but in the middle, there's actually not a lot known there."

ALERT AND ALARMED

Recent research has shown that yellow-legged gull (*Larus michahellis*) embryos perceive the alarm calls of adults that alert them to the presence of predators such as mink.

As a result, the embryos alter their behaviour inside the egg, delaying their hatching, calling less and vibrating more to alert nearby siblings.

Once hatched, the chicks are smaller and more prone to crouching when they hear alarm calls than chicks that weren't exposed to alarm calls as embryos. Call-exposed chicks also have shorter telomeres and elevated levels of global DNA methylation and stress hormones such as corticosterone, among other changes.

As adults, birds that develop under the chronic stress of predators reproduce less and die younger.

Tracing mechanisms

To better tackle the "how" of acoustic developmental programming, Mariette's zebra finch team recently gained a new member when Julia George, a neurobiologist at Clemson University, in the US, joined in 2020 to lend a genetic eye to the behavioural findings. "Our hypothesis is that there are two phases to the developmental reprogramming," she says. "First, there would be the initial response – how the birds respond to the stimulus of the heat call. . . . And then the second part is how you go from that acute response to more persistent changes that affect the development of the birds so that they will be more tolerant to heat as they grow."

"I have a signal, which I think is really different between the heat call – exposed animals and the animals exposed to control calls. I'm excited that there's this difference … but I can't really interpret what it is yet."

Such responses wouldn't be unprecedented. A couple of years ago, researchers studying yellow-legged gulls (*Larus michahellis*) – long-lived, colonial seabirds that lay clutches of three eggs – documented increased global DNA methylation among chicks in artificial lab clutches that heard adult gull alarm calls as embryos, along with higher levels of the stress hormone cortisol and fewer, smaller mitochondria (indicatory of lower energy production) compared with controls. There were behavioural changes too: chicks that heard the calls from within their eggs delayed their hatching, and while still in the egg, vocalised less and vibrated

The embryos within the eggs of certain turtles and snakes (top right) communicate with each other to synchronise their hatching, to evade predators. Embryos of the yellow-legged gull (main photo) listen for their parents' alarm calls.

ABOVE: DAVID SANTIAGO GARCIA / GETTY IMAGES

RIGHT: WLADIMIR FAÉ WFAÉ / GETTY IMAGES. COULANGES / SHUTTERSTOCK.

more, perhaps to share information quietly. After hatching, these chicks were also quicker to crouch upon hearing the alarm call.

Importantly, these developmental and behavioural changes were shared by all three of the hatchlings even when only two eggs were exposed to the alarm calls during the experiment, likely because the siblings were moving inside their eggs and rubbing the shells against one another when predators were near. Study co-authors Jose Noguera and Alberto Velando, both evolutionary ecologists at the University of Vigo in Spain, say they expected some level of information trading among the eggs. But Velando notes that "the extent to which the non-exposed chicks showed the same responses as their exposed siblings was quite surprising."

Chicks that heard their parents' alarm calls from within their eggs delayed their hatching, vocalised less and vibrated more, perhaps to share information.

In a 2019 *Nature Ecology and Evolution* commentary published alongside the yellow-legged gull study, Mariette and her Deakin University colleague Katherine Buchanan wrote that the findings "suggest a degree of developmental plasticity based on prenatal social cues which had hitherto been thought impossible."

Even as they urged further studies to follow the long-term effects of these developmental changes, they added that the work is "pivotal in redefining avian embryos from passive subjects isolated from the outside world, to well-informed players, responding to diverse social cues in their external environment." ◉

AMANDA HEIDT is a marine scientist and science communicator. This piece first appeared in *The Scientist* the-scientist.com

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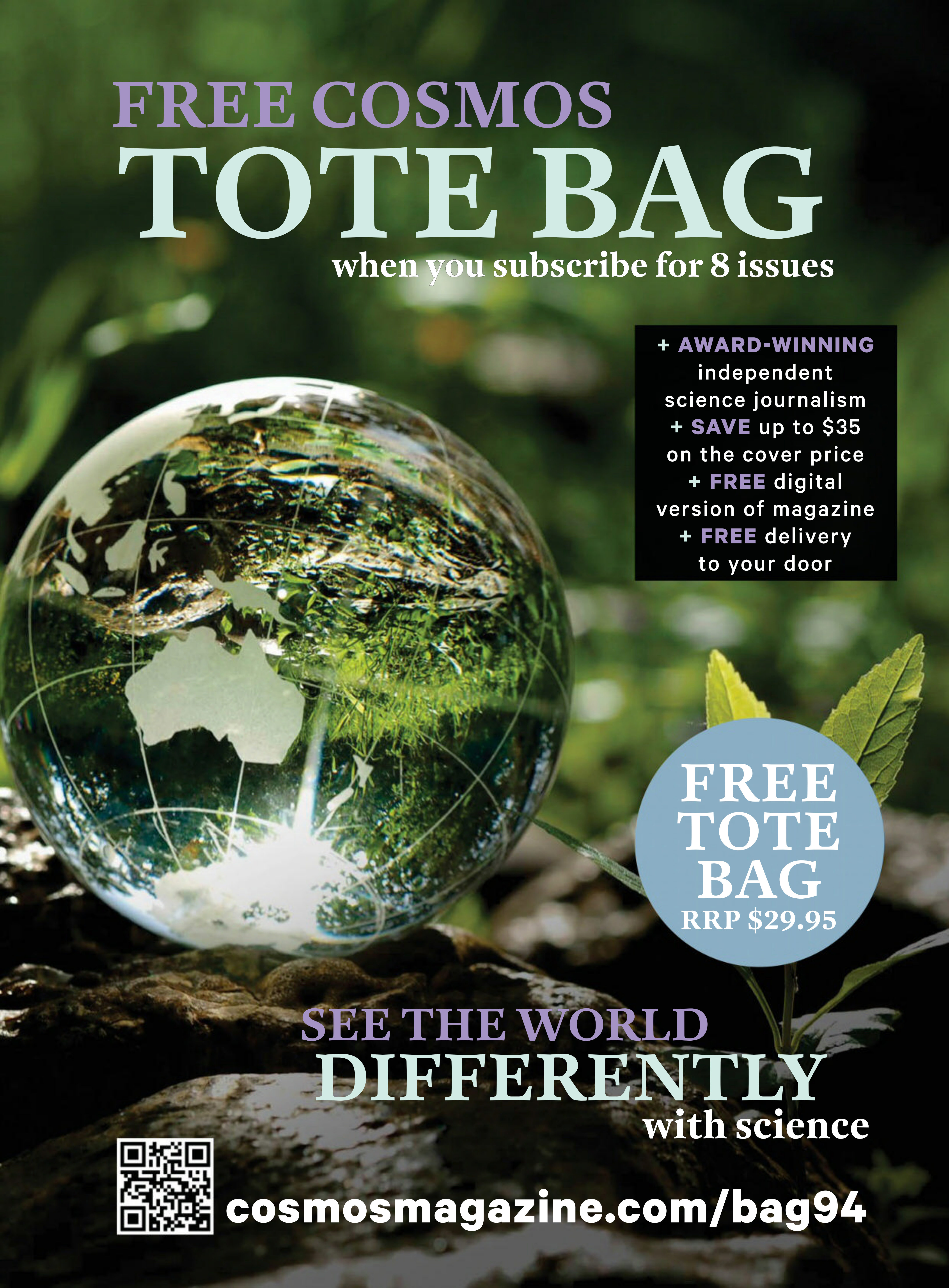
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A Whitney Houston facsimile is projected onto the stage in Madrid, Spain, in 2020, continuing a showbiz trend. Although these are called holograms, the technology is both older and newer – and not actually a hologram at all. Read more on page 98.

ALDARA ZARRAOA / GETTY IMAGES

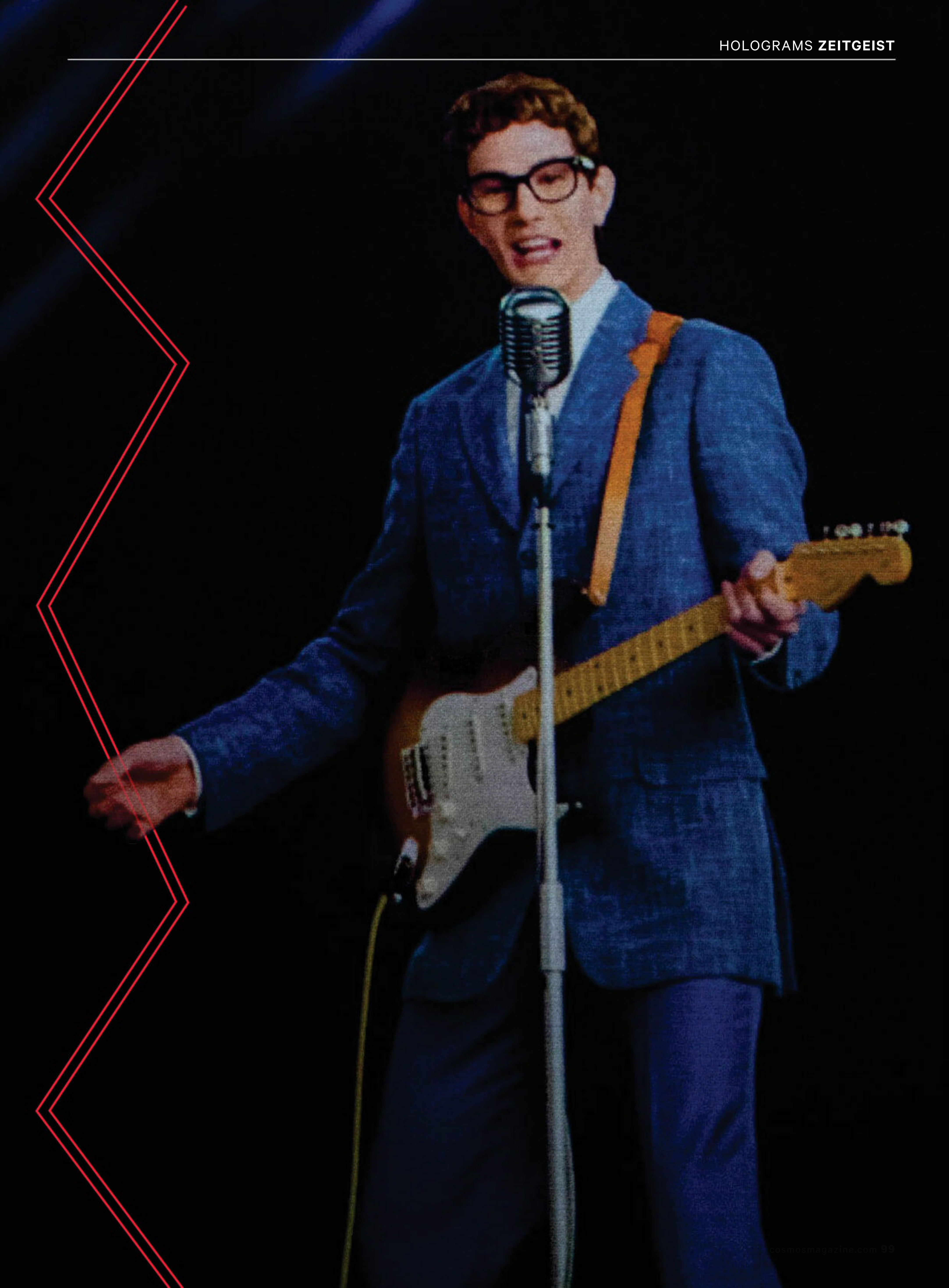
ZEITGEIST

SCIENCE MEETS LIFE

HOW DO YOU STAGE A HOLOGRAPHIC CONCERT?

From speeches by long-dead football coaches to concerts from legendary musicians still very much alive, what does it take to create and present a holographic performance? **AMANDA YEO** nails down the facts.

ALDARA ZARRAOA / GETTY IMAGES



On the night of 15 April 2012, American rapper Tupac Shakur appeared to grace the stage at the Coachella Valley Music and Arts Festival in California – 16 years after the artist was killed in a drive-by shooting. Performed in front of 90,000 people, Tupac's holographic set was the work of American visual effects production company Digital Domain.

"It was a tribute to him," said Digital Domain's then-chief creative officer Ed Ulbrich. "No one was making money off him. It was done with the blessing of Tupac's mother."

Virtual Tupac quickly went viral around the world, garnering cautiously awed reactions. While some expressed concerns about the ethical implications surrounding the animation of a dead celebrity, others excitedly speculated about what such holograms might mean for the future of entertainment. Yet almost a decade later, holographic performances remain relatively novel – and how they are created is still a mystery to many.

What we're talking about when we talk about holograms

From Princess Leia's plea in *Star Wars: A New Hope* ("Help me, Obi-Wan Kenobi…") to AI assistant Cortana in the *Halo* video game series, holograms have been a staple in science fiction for decades. But our understanding of exactly what constitutes a hologram hasn't always been the same. While it was an impressive use of technology – and no doubt influential – Digital Domain's Tupac hologram wasn't even technically a hologram in the strictest sense of the word.

"The term 'holography' was originally coined to describe a particular technique to record images that would also provide different perspectives from multiple viewing angles," explains CSIRO's Craig James. A senior researcher at CSIRO's Sustainable Mining Technologies group, James helps the organisation's research teams develop extended reality experiences such as "holograms" for educational purposes.

"Today, the use of the term 'hologram' is more widely used to describe technologies where a viewer can see an image of a subject that isn't physically there, without visible electronic or projected screens," James says.

"While the marketing term is called 'holographic', at its core, the projection of a fabricated performance is still two-dimensional in nature," says Aruna Inversin, a creative director at Digital Domain. "The performer looks holographic in part because of its juxtaposition with a real performer on stage."

These holograms can't quite match the fictional hologram technology dreamt up in sci-fi classics, which project images onto thin air. However, the invisible screens used to create our real-world "holograms" make them the closest we've managed to achieve.

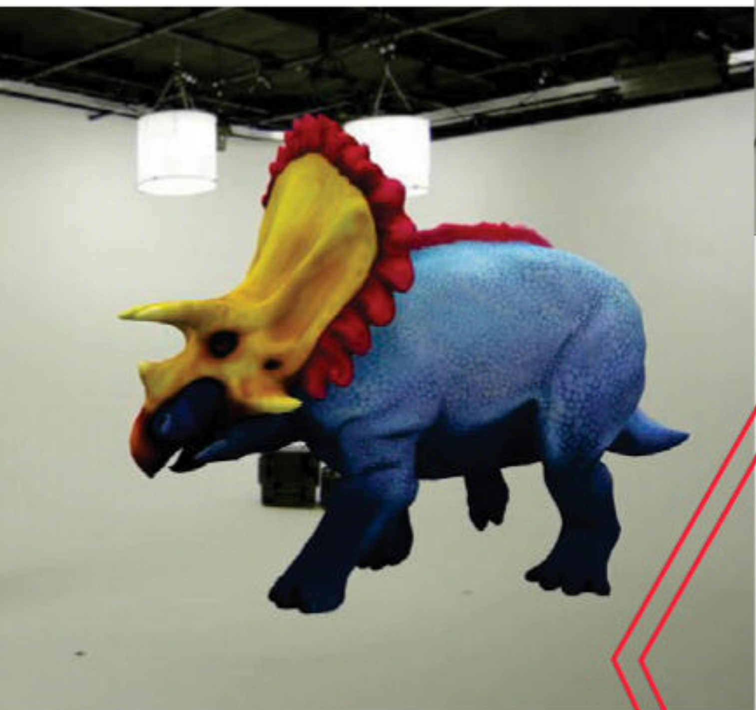
Putting on a show

Advancements have facilitated considerable innovation in hologram generation, however the most commonly referenced method remains the use of Pepper's ghost.

Named after the British scientist who popularised it in the 1860s, Pepper's ghost is an optical illusion created by projecting an image onto a transparent, reflective screen such as a pane of glass. When this screen is erected between a stage and its audience, both the reflection and the live scene behind it are visible to viewers (see box, opposite).

"The original illusion used half-silvered mirrors that allowed a ghostly image to appear beside a live performer," says James.

"Current performances typically use tightly stretched, transparent films and high-resolution, laser-powered



Through some nifty technology, renowned palaeontologist Jack Horner was able to front a staged show bringing dinosaurs to (a kind of) interactive life. But is it a true hologram? Or illusion?

BASE HOLOGRAM X3

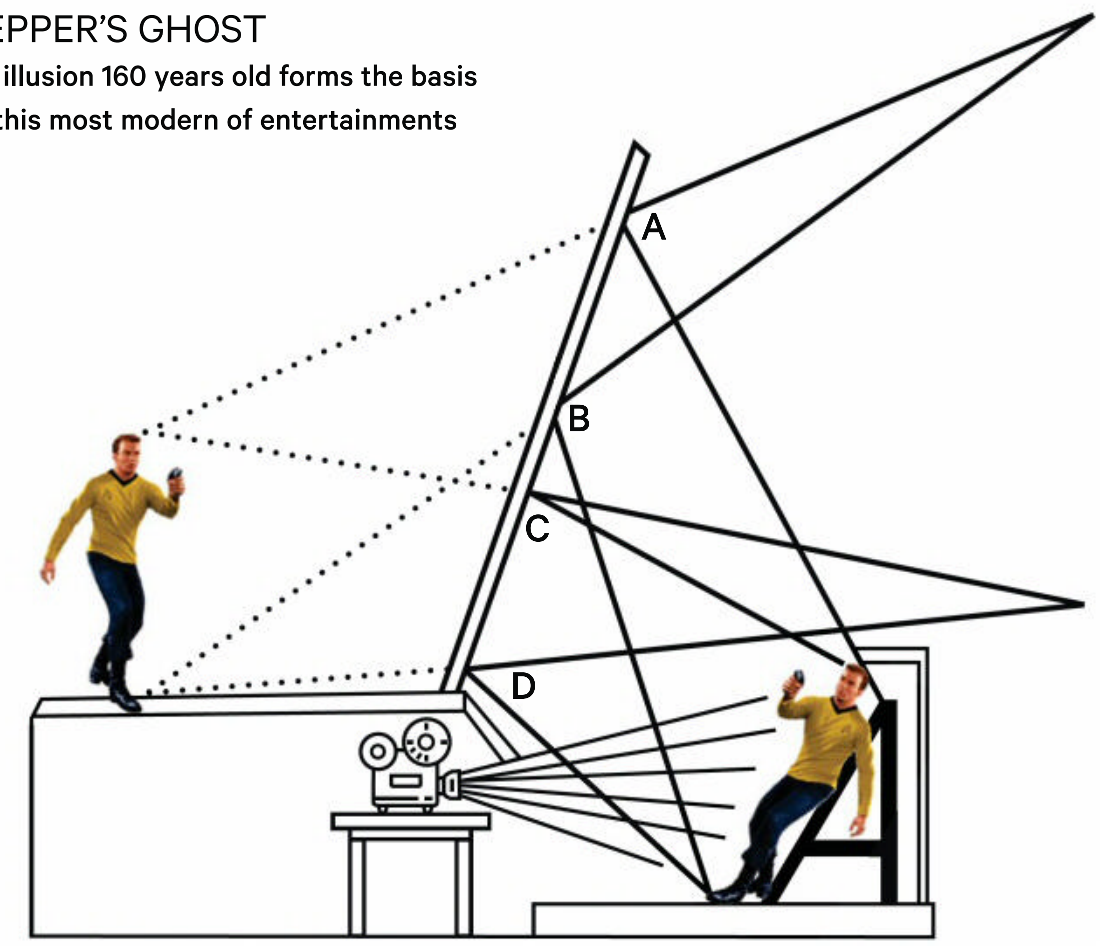
projectors that provide very crisp, true-to-life images while still allowing audiences to see the background stage details." This more modern method is currently used by both Digital Domain and BASE Hologram, the production company behind performances such as The Whitney Houston Hologram Tour in 2020 and Jack Horner's Dinosaurs: A Holographic Adventure in 2019.

"While Pepper's ghost and variations on the technique do not provide a true hologram that can be seen from all sides, the audience is typically far enough away from the stage that a single perspective is sufficient to preserve the illusion that a holographic performer is present on the stage," says James. "The screen being used is also typically arranged so that other 'live' performers on the stage are able to interact by walking in front of or behind the 'hologram'."

"The general idea of Pepper's ghost has remained the same, but the technology has drastically improved," says Inversin. "For some of the most well-known holographic presentations, the display is relatively easy. The real trick is creating the performer, which requires skilled artists."

PEPPER'S GHOST

An illusion 160 years old forms the basis of this most modern of entertainments



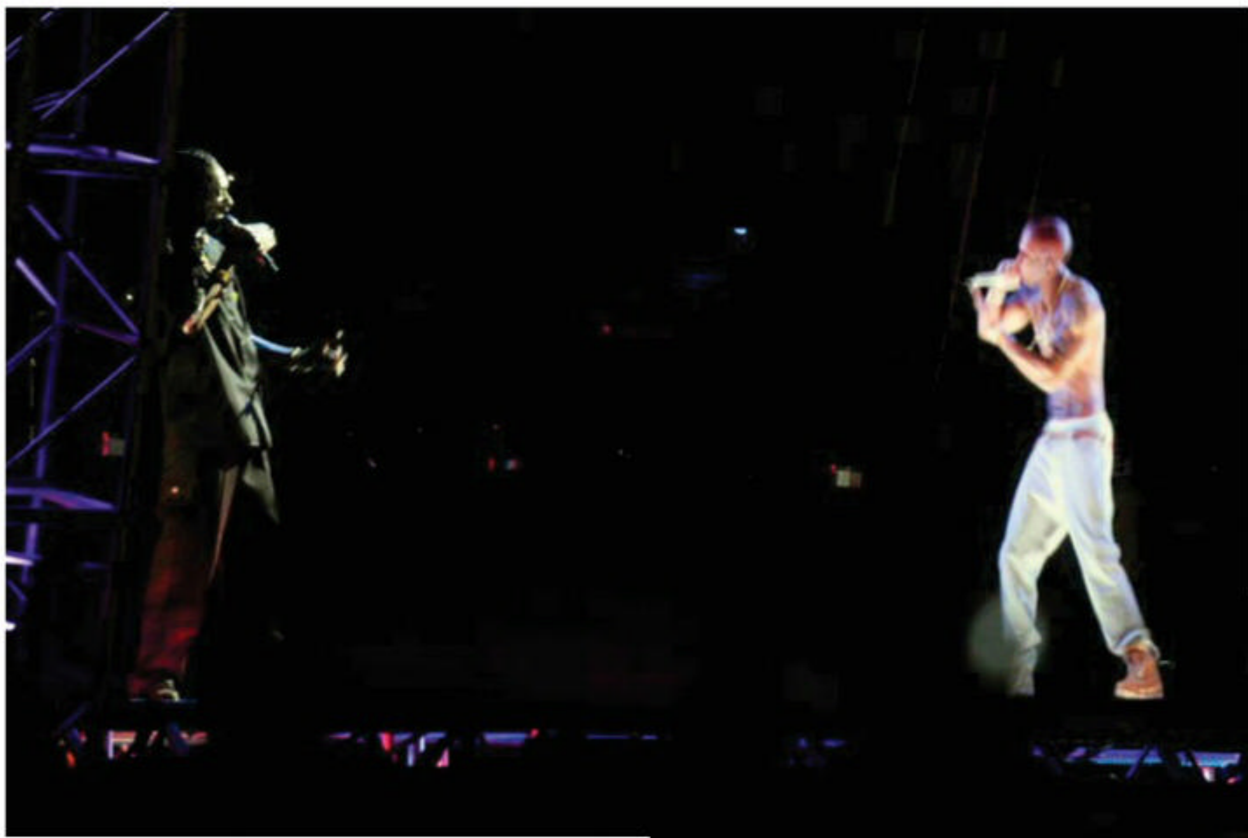
Light reflecting off a concealed actor (bottom right) creates the illusion of an incorporeal body on the stage (top left). Light shone onto the actor bounces off at different angles to hit an angled plate of glass: A, B, C and D are examples of points where the light both refracts through to form the phantom image behind the glass (dotted lines) and bounces off the glass towards the audience (solid lines).

Crafted for the stage

Not all videos can be turned into convincing holograms. Though archival footage provides reference material for creating digital performers, the video typically isn't suitable for turning into a hologram itself, and not just due to resolution issues. For a successful holographic display, the person or object needs to be filmed while isolated on a blank backdrop, ensuring background elements aren't also projected into the scene. Further, the lighting in the recorded footage needs to be matched to that of the live stage in order to maintain the illusion.

"It wouldn't make sense to show a video of someone in full sunlight on a stage at night, for example," says James.

"The projected video for holographic concerts has to be created from the ground up specifically for this purpose. Actual



Back from the dead? Tupac Shakur's music – and image – was revived back in 2012, left; Maria Callas became a hologram in Paris, below, in 2018; Whitney Houston took the stage in Madrid, below left, in 2020.

An educational resource for this story is available at **www.education.australiascience.tv**

CREATING A HOLOGRAM OF A LIVING PERSON IS MUCH MORE STRAIGHTFORWARD THAN RENDERING ONE WHO HAS DIED

actors form the basis of these productions, in combination with motion capture, CGI and other production techniques," says BASE Hologram CEO Brian Becker.

Footage of a hologram's subject is created by filming a body double in front of a greenscreen, as well as motion-capturing their performance. The video of the actor is then augmented with a digital avatar of the subject, puppeted by their motion-tracking data. The combination of these elements creates a realistic video which can then be projected onto a transparent surface to turn it into a "hologram".

"For the Tupac Coachella performance, we started with a live stand-in, who matched Tupac's physical build and could replicate (to a degree) his musical prowess and stage performance," Inversin says. "We then recorded him against a greenscreen and meticulously tracked his head.

"For this type of performance, our team pairs our facial capture technology with a head mounted camera to capture the stand-in talent's facial performance. The actor can then drive the digital head. Our artists then created a digital version of Tupac's head using reference material and matched the digital version with the performer. From there, additional facial animation can be applied to serve the creative needs of a performance."

Deeper and faker

Deepfake technology appears to be the perfect match for hologram performances. Using machine-learning AI, this technology can create deceptively realistic computer-generated images that are indistinguishable from reality to the average observer. Even so, deepfakes haven't yet become a widespread tool in hologram production, which still largely relies on artists' "analogue" efforts.

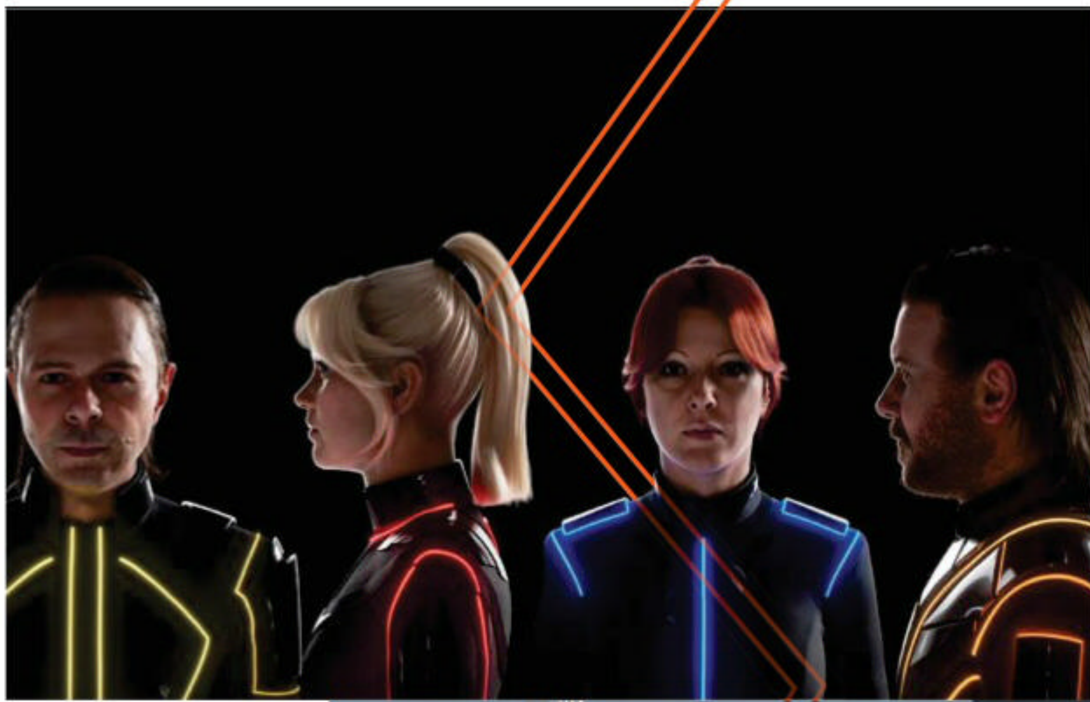
Still, machine learning is beginning to creep into the hologram industry, with Digital Domain recently introducing their tool Charlatan.

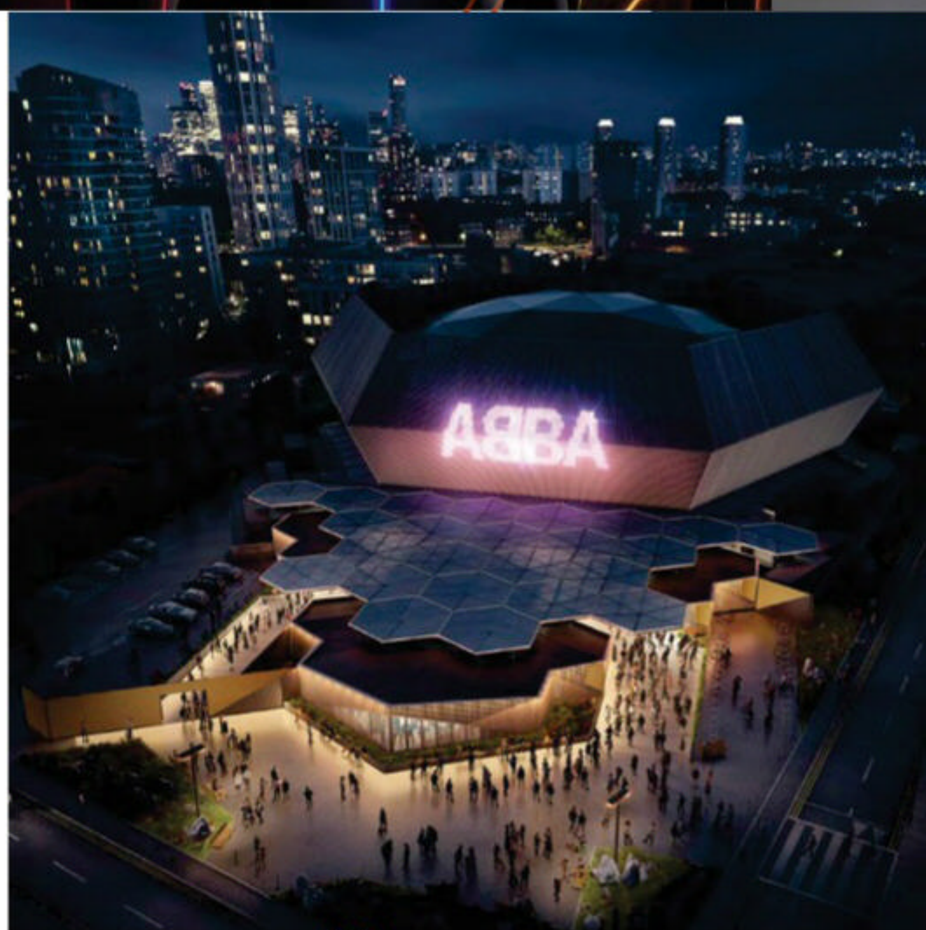
"Charlatan is a face-swapping tool that uses machine learning to help create realistic digital versions of characters," says Inversin, noting that it was deployed to digitally recreate NFL coach Vince Lombardi for Super Bowl LV.

Digital Domain fed Charlatan videos of Lombardi, which the machine-learning tool used to create a digital model of the coach. Lombardi's avatar was then animated with motion-captured facial movements and overlaid on live action footage of an actor.

"Charlatan allows our team to use 2D neural rendering layers to create facial performances, without using an existing digital model," says Inversin. "In the case of Lombardi, we were able to use 2D reference images as a starting point. Live action performers are then augmented with the new face."

FROM LEFT: JEFF KRAVITZ, ALDARA ZARRAOA, NATALIE HANDEL / GETTY IMAGES





Here we go again: ABBA's upcoming tour features only holographic figures, above left, appearing as they did in the 1970s, moving via motion-capture data gathered from the group as they performed their latest music, above right.

BASE HOLOGRAM X3

Honouring the dead, celebrating the living

Though hologram performances are most famously used to recreate an artist who has died, this is not always the case. ABBA's upcoming Voyage concert plans to utilise holograms to make the Swedish pop group appear as they did in the 1970s, at the height of their popularity – as well as save them from having to physically perform on multiple nights.

Fortunately, creating a hologram of a living person is much more straightforward than rendering one who has died. This is because rights issues in such cases are less complicated, and any reference material can simply be created.

"In the ABBA show, the performers were available to provide motion capture data to guide their on-stage 'holograms'," says James. "While the holograms were digitally crafted by a team of artists, the motions and voices represented on stage would be drawn directly from the singers' pre-recorded performances."

Despite this, hologram concerts are best known for channelling deceased entertainers. Becker stresses that he doesn't consider BASE Hologram's work to be "bringing back" dead artists, but rather paying tribute to and celebrating them. Both he and Inversin note that their performances are created with the collaboration and approval of those who own the rights to the recreated person's image, such as their families or estates.

"Every attempt is made to be authentic and true to the artist, with some modifications to how the artist may perform in today's day and age," says Becker. "The main interest in these types of shows are to preserve the legacy of these one-of-a-kind musicians and give fans the chance to see them perform – many for the first time."

Inversin says it typically takes Digital Domain six to nine months to put together a show. The size of the creative crew can stretch into the hundreds, with modellers, animators, riggers and deep-learning engineers just a few of the teams needed to create the digital performer.

"Creating a virtual human requires a lot of people, regardless of whether it is focused on just a head replacement, as with the Tupac hologram, or if it needs a full digital performance," says Inversin.

An approaching mirage

Almost 10 years after Tupac's Coachella performance, holographic concerts are still an emerging medium, but one with significant potential.

"When international movements are restricted, or if there are personal reasons that limit performers' availability, this form of event could provide an option that would otherwise prevent staging a local performance," says James. "We already have instances where audiences watch remote stage performances through large screens, so ultimately it would be up to the fans of the performers to determine if holographic events give a convincing concert experience."

A hologram isn't the same as the real thing. Still, it might get close enough.

AMANDA YEO is a Sydney-based writer and co-creator of tech podcast Queens of the Drone Age. Her most recent story for Cosmos, on drones, appeared in Issue 91.

STICKY BUSINESS

Ever wondered why some things are sticky and others aren't? Applied mathematician **SOPHIE CALABRETTO** explains the chemical attraction of garlic and the magic of tackifiers.

As someone who loves all things fluid, it seems strange that it's taken me until this year to wonder about stickiness and the mechanisms that control it. It seems like a trite observation, but lots of things are sticky – foods, plants, the eponymous tape. It's been something I've taken for granted.

But is all stickiness the same? And are any solids truly sticky, or does the stickiness result from a sticky surface fluid?

My inspiration came as I was chopping fresh garlic. It turns out that the stickiness I felt comes from mercaptans, sometimes lovingly referred to as "thiols". These sulphur-containing compounds are attracted to other sulphur-containing compounds such as the amino acid cysteine, which can be found in our hair, nails and skin.

When those fresh garlic mercaptans come into contact with the cysteine in your skin, they form a strong bond. Think of this intermolecular bond as you would magnetism: you can't really "see" the bond, but you can feel it.

This chemical attraction is what creates the physical sensation of stickiness on your fingers, and the stronger the bond, the stickier it will feel.

After gin, my second favourite substance is sugar which, by itself, is not sticky. White sugar, in its crystal form, is made of carbon, hydrogen and oxygen atoms, and when these relatively large molecules are dry and intact, they're pretty impervious to each other, thanks to those strong internal oxygen-hydrogen bonds in their crystalline lattice. But with the addition of water, everything gets more complicated. The oxygen atoms around the outside of the sugar molecules have a

(ALL STICKY NOTES) OLIALE72 / GETTY IMAGES

PANNONIA / GETTY IMAGES

slight negative charge; when dissolved in liquid, the sugar molecules disperse and those oxygen atoms are attracted to the hydrogen atoms in the water, which have a slight positive charge, because opposites attract – except on dating apps.

This chemical attraction is an example of hydrogen bonding and, although it's not the strongest of the chemical bonds, it's still enough for the sugary liquid to feel sticky.

"But my hands get all sticky when I touch fairy floss, and that's dry!" I hear you proclaim. While it's true that fairy floss is essentially many, many thin strands of molten sugar that have re-solidified as they're spun up into a delicious mass, it sticks to you because your skin is covered in about three million sweat glands, and the average person sweats up to 5.6L per day. (Even if you're not moving around that much, you're looking at over 3L of daily sweat.) We're all sweaty, all the time, almost everywhere. Unfortunate, I know.

Bio-sticky

Stickiness gets quite dramatic in the plant world. I love the excitement of a carnivorous plant trapping its prey – and many of these flesh-eating botanical marvels, such as sundews, are excellent sticky-makers. Sundews produce glistening drops of sticky, sweet mucilage (yes, a lot like mucus) to attract and entrap their prey. Their prey either dies from exhaustion trying to escape, or asphyxiation as the mucilage envelops them (gross). This bio-adhesive is a polysaccharide substance, containing long chains of monosaccharides – aka simple sugars. We know what happens when we have a whole lot of sugar plus moisture … stickiness!

But do not worry, dear reader – not all mucilage is used for evil. That delightful gooey substance inside aloe vera that you may rub on your sunburn is also mucilage. Some plants are good people.

Glue trap

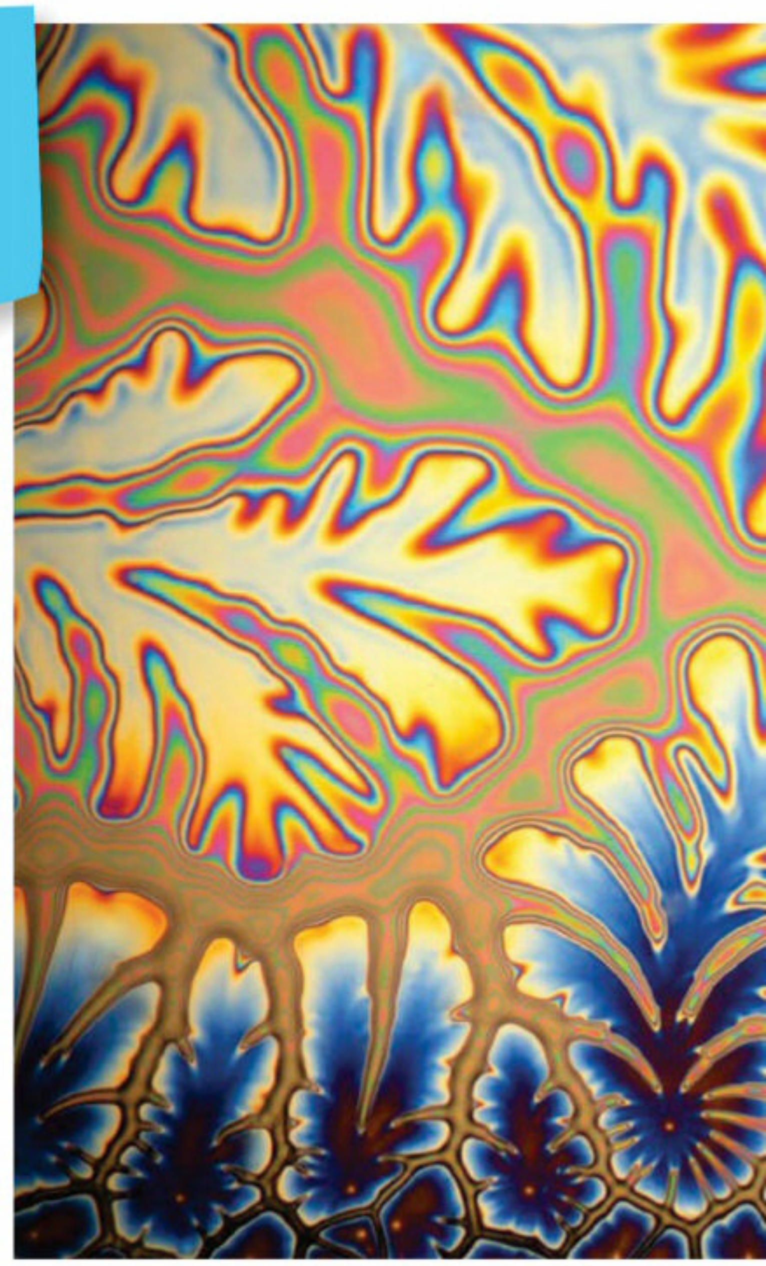
Of course, we can't talk about stickiness without referring to glue and adhesives: substances with the sole purpose of bonding things together. Adhesives come with a whole gamut of sticking methods, including drying (solvent-based and polymer dispersion adhesives), pressure (pressure-sensitive adhesives), contact adhesives, hot-melt adhesives and numerous others. But their sticky feeling is just a manifestation of their bonding process.

I'm less interested in how to accidentally glue my fingers together than I am in things that feel sticky when I touch them, so let's talk about the kinds of adhesives that release their grip when I stick them to myself, like duct tape and Post-its. These are called "soft adhesives" and are a type of pressure-sensitive adhesive (PSA).

PSAs are usually composed of an elastomer – which is a polymer with viscoelasticity – often paired with a delightfully named "tackifier", which is not only a compound used to increase the tack or stickiness of an adhesive's surface but also my new favourite word.

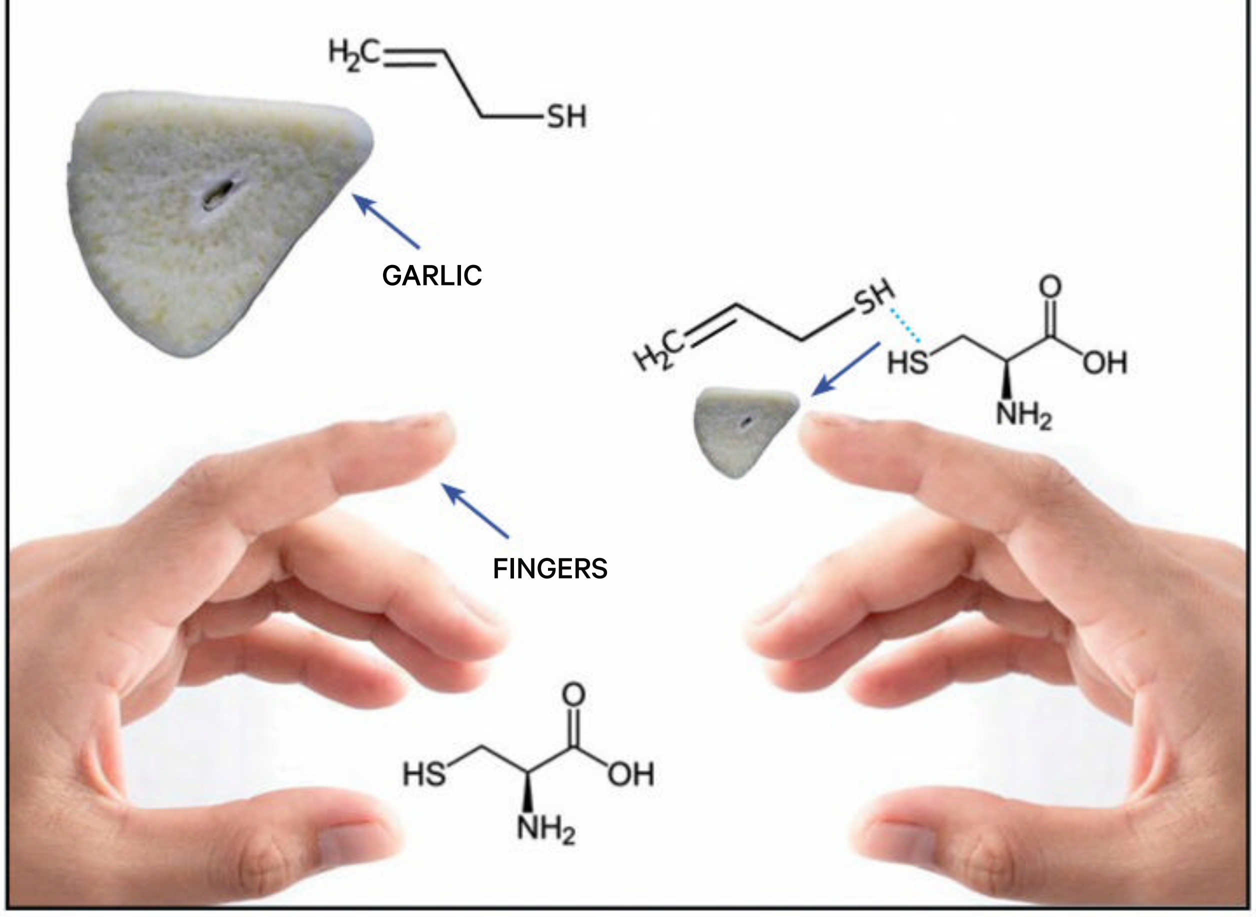
Viscoelasticity means that, when deformed, a material exhibits properties of both a viscous fluid – thick molasses, for example – and an elastic solid, like a rubber band. Viscosity describes a fluid's

Streaming patterns like this are characteristic of the Saffman-Taylor effect.



ATTACHED TO GARLIC? HERE'S WHY

The mercaptans in garlic are sulphur-containing compounds that (no surprise) obey the rules of science – and are attracted to other sulphur-containing compounds. Like cysteine, for example – an amino acid present in our skin, nails and hair.



LEFT: AR DUCHA MISFA'I, ISSARAWAT TATTONG / GETTY IMAGES. ABOVE: CLAIRE TREASE / WIKIMEDIA COMMONS.

A damselfly in a sticky situation, trapped by a sundew's simple sugars.

resistance to movement (the higher the viscosity, the larger the force needed to make it flow), and elasticity describes a solid's resistance to deformation – for example, how much force you need to stretch that rubber band.

Viscoelastic materials can have elements of both of these properties, depending on the magnitude and the timescale of the stress being applied. This is very important for soft adhesives, because there needs to be a balance between flow and resistance for bonds to form and create adhesion.

Unstuck?

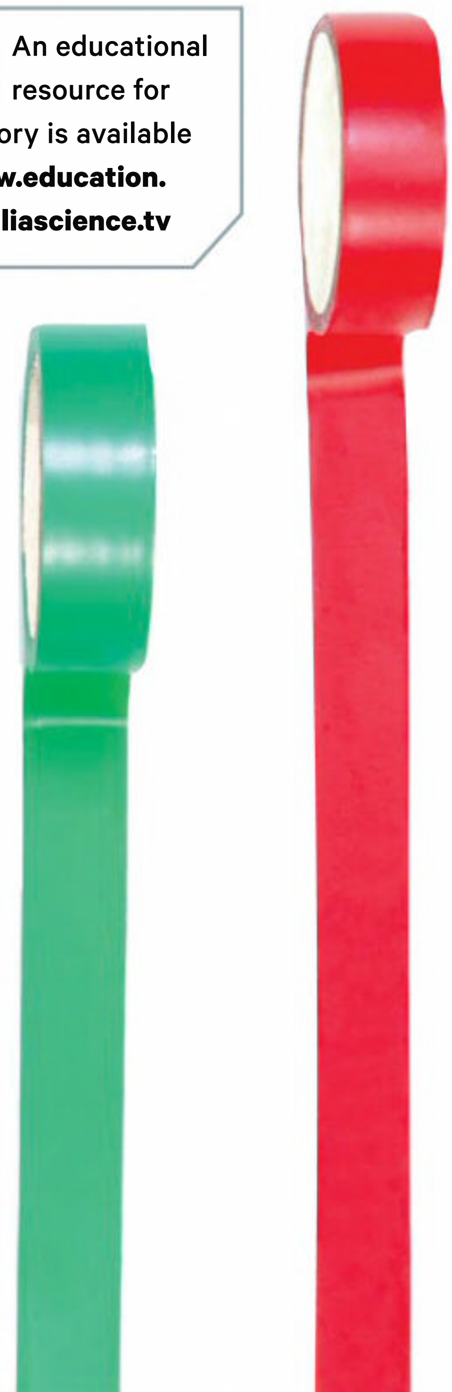
There are two very distinct ways in which they can unstick: either exactly like a solid or exactly like a fluid, with absolutely no crossover between them.

When you unstick a solid, a very thin slice of air appears between the adhesive solid and the adhering surface, breaking the bonds between the molecules in a way that does not deform the solid. Think of when you rip that picture hook off the wall – the adhesive strip doesn't deform, and pulls away the layer of paint, which is more strongly bonded to the adhesive than to the layer of paint below.

Unsticking a liquid, on the other hand, sees very extensive deformation of the liquid adhesive, and air enters and breaks the bonds in a Saffman-Taylor-like behaviour (which creates a finger-like pattern in liquids with different levels of viscousness). This kind of unsticking is like removing your picture hook by pulling the tab at the bottom so the tape deforms and comes away neatly.

It turns out that stickiness is more amazing than I thought – and it all comes down to the physical effects of chemical bonding. Speaking as a mathematician, I was going to make a chemistry joke – but I'm afraid I won't get a good reaction.

An educational resource for this story is available at **www.education.australiascience.tv**



SOPHIE CALABRETTO is a mathematician specialising in fluid mechanics, and Honorary Associate Professor at the ACE Research Group, University of Leicester. Her story on sharks appeared in Issue 89.

Q&A

Over the past few months, through newspapers around Australia, *Cosmos* has asked readers to send us their secret science stumpers, to see how we go finding answers to your curliest questions. In this and coming issues, we present our findings, enlisting the insights and brainpower of Australia's leading scientists along the way.

Q

My 6-year-old son randomly asked me: How many people can fit into Australia?
– Hannah

Australians all let us squeeze in . . .

PETERPENCIL / GETTY IMAGES

A

This is an interesting question because there are so many different approaches we can take to find an answer to it. Let's try some different models.

The most *efficient* way to fit people into Australia – the way we might best fit people into a phone box, for example – is to make them all stand erect together, shoulder to shoulder, back to front, packed in like standing sardines.

According to the body proportions detailed by American sculptor Avard Fairbanks, the adult male has a shoulder width of around 45.7cm and an adult female of around 36.6cm.

Because the dimensions of a male and female adult human differ slightly, we've based our calculations on a 50:50 ratio of males to females. Australia is 7.69 million square kilometres in area, so if we use the human sardine model we'd fit 39 trillion – 39,000,000,000,000! – people into Australia (as long as we build platforms over all the lakes and rivers).

But that's not enough. What if we stacked people on shelves, on top of each other? If each shelf was 2 metres tall and we stacked them all the way up to the edge of the breathable atmosphere (which in itself is an interesting question, but which we're going to decree as 6,000km above the surface), we could add 3000 times more flat-packed humans – and fit a 117 quadrillion people into the country (117 quadrillion seconds is the same as 31.7 million years; the earliest record of humans is around 5.7 million years ago).

You'll have spotted the problem here: the sardine solution (single or stacked) won't be acceptable under free-range chicken rules, where there can only be 10,000 hens per hectare. Based on this, we could only fit approximately 7.69 quadrillion humans and remain within legal free-range limits – but at least it'd be RSPCA sanctioned (and more likely to produce good-quality eggs).

But – getting to the important point – the issue is whether Australia could *sustain* all those people. People need resources – like food and water – so that's a bigger limiting factor than space alone. Australians consume a lot of resources, even though Australia is very large.

"If everyone in the world started living and consuming and producing waste like an average Australian, then it would take the equivalent of four planet Earths to sustain them," says Gour Dasvarma, Associate Professor of population studies at Flinders University. "But considering all possibilities it may be stated that about 40 million people could live in Australia.

"Of course, this does not mean Australians should go on consuming more and creating more waste; on the contrary, Australians should strive to reduce their ecological footprint in consideration of the worsening climate and food production crisis of the world."

Just out of interest: what if Australia's population was merely the equal of one of the world's most population-dense places? The World Bank estimates Singapore has 8,019 people per square kilometre (let's call it 8,000 – easier maths). That density would have Australia's population at about 63.7 billion people: not as many as our sardine solution, but still more than eight times the Earth's current population. Breathe in!

Deborah Devis

Q

Why don't people who snore wake themselves up with their snoring?

– Sue

A

Ask any snorer why their sonorous rumblings don't wake them up and they will almost inevitably give the same, simple response: "Why ask me? I don't snore!"

A snorer's blissful ignorance of their own sounds gives the impression that they must sleep soundly through them, while the rest of the household listens on in frustration or horror. But just because they don't remember waking up doesn't mean they sleep like a baby. To explain why, we need to look at why some of us snore in the first place. Let's break it down.

Why do we only snore when we're asleep?

Your mouth and throat are full of all sorts of soft, floppy bits, such as your uvula, tonsils, adenoids and other bits of tissue.

When we're awake, your body holds all these bits in position, ready for action. But when we fall asleep, our muscles relax and everything is free to loosen up.

This relaxation is an important part of sleep. As well as allowing our bodies to rest and recuperate, partial muscle paralysis prevents us from acting out our dreams and walking. While a live action mime of our dreams could be an amusing insight to spectators, it could also be dangerous.

As well as keeping our limbs safely tucked in bed, sleep relaxation affects the muscles that hold everything in place. For some people, this relaxation is enough for the soft tissues in their mouths to flop into undesirable positions and partially block the flow of air as they breathe.

Snoring is the resulting sound of all the oral smooshy bits vibrating and slapping together as air forces its way through the obstruction when we breathe.

Evolution has set us up to be snorers

Those mouth parts that cause all the trouble are actually the result of human evolution. A perfect anti-snoring airway would be a long, straight tube with no soft parts at all. Unfortunately, a lot more is required of our airways than just unlaboured breathing. In order to vocalise beyond simple grunts, faces and throats have been shaped to

MIREKP / GETTY IMAGES

accommodate more sophisticated sound apparatus – most of which is soft tissue. Our tongues have migrated back into our throats to shape different sounds. Compared to other mammals, our tongue rests precariously close to the back of our upper airway – the perfect place to become a blockage when we snooze.

Our upright posture has also had an effect, shifting throats underneath skulls and leaving less room in which to fit all those squishy bits – prime conditions for the airway obstruction that leads to snoring.

Loud sounds wake us up. Why not snores?

A loud crash from the kitchen in the middle of the night is almost certain to wake us up. Whether it's a tree falling or a pet's overly ambitious adventure, human bodies react to the sound by snapping speedily into a state of awareness.

This is because our ears are still taking in sound while we're asleep, and our brain is still processing . Brains prioritise restfulness while we sleep, filtering out low-priority sounds and letting us snooze through unimportant background noise.

Only high-priority signals trigger wakefulness: research has shown we're more likely to respond to unusual sounds, especially loud sounds that could signal danger, and someone speaking our own names.

For the offending snorer, the brain interprets soft snores as innocuous background noise that needs no further attention. But what about the ones that rattle the roof shingles? In fact, very loud snores actually *can* wake the snorer, but only briefly. We usually need to be in a very deep sleep state for our muscles to be relaxed enough for snoring to start, and at that point our brains are shutting out all but the most important information.

Even if a snore is thunderous enough to make it through this filter, the snorer slips right back to sleep within seconds. Brainwave research suggests that we can have up to 25 of these "microarousals" per hour without even noticing.

Jamie Priest

DIMITRIS66 / GETTY IMAGES

Q

How does popping candy work? – *Jennifer*

What causes that characteristic crackle?

A

If you've upped your lolly intake over **recent months (we certainly have** at ***Cosmos*), you may have tried** some **popping candy. It's a treat and a** science **experiment all in one, causing a** tingling **sensation on the tongue and a** delightful **crackle as you eat it.**

But what causes that popping sensation?

You might think it's a chemical reaction, but it's actually a pretty cool combination of gases and heat. Precise recipes vary from brand to brand, but popping candy is typically a mixture of a few different types of sugar, and tiny pressurised bubbles of a gas, usually carbon dioxide. For this reason, it's also referred to as "gasified candy" in some patent applications.

The gas is added to melted sugar at a high pressure – at least two or three times typical air pressure at sea level, and sometimes much higher. With the right combination of temperature and pressure, the sugar forms small crystals, each containing several gas bubbles roughly a tenth to a fifth of a millimetre in diameter. Sugar dissolves in water, so when the candy makes contact with your tongue, the water in your saliva breaks up these bubbles. The pressurised gas escapes, sometimes with enough force to crack the rest of the candy crystal. This is what causes the tingling, popping sensation.

Both the bubbles and the crystals are very small, so the amount of force involved in these cracks is unlikely to cause any problems. But in a small amount of bad news, at least one lab-based study has found that popping candy can have an effect on tooth enamel.

If you want to watch gasified candy pop but are concerned about your teeth, you can add it to plain water instead – this will also set it off.

This is particularly good news, because it means that popping candy can be used in chemical reactions. In 2021, a group of Chinese and Australian chemists used popping candy to extract some key molecules from vinegar and two alcoholic drinks: beer and baijiu, a liquor made from fermented grain.

The carbon dioxide released by the popping candy proved to be the perfect way to agitate the mixtures and disperse the relevant substances. Because it uses edible sugars, the method is more environmentally conscious, and leaves the ingredients safe to ingest at the end.

This research paves the way for a range of potential applications in pharmaceutical or food additive manufacture.

Ellen Phiddian

To read more questions and answers – or to ask us one yourself! – visit cosmosmagazine.com by scanning this code

WHERE IN THE COSMOS?

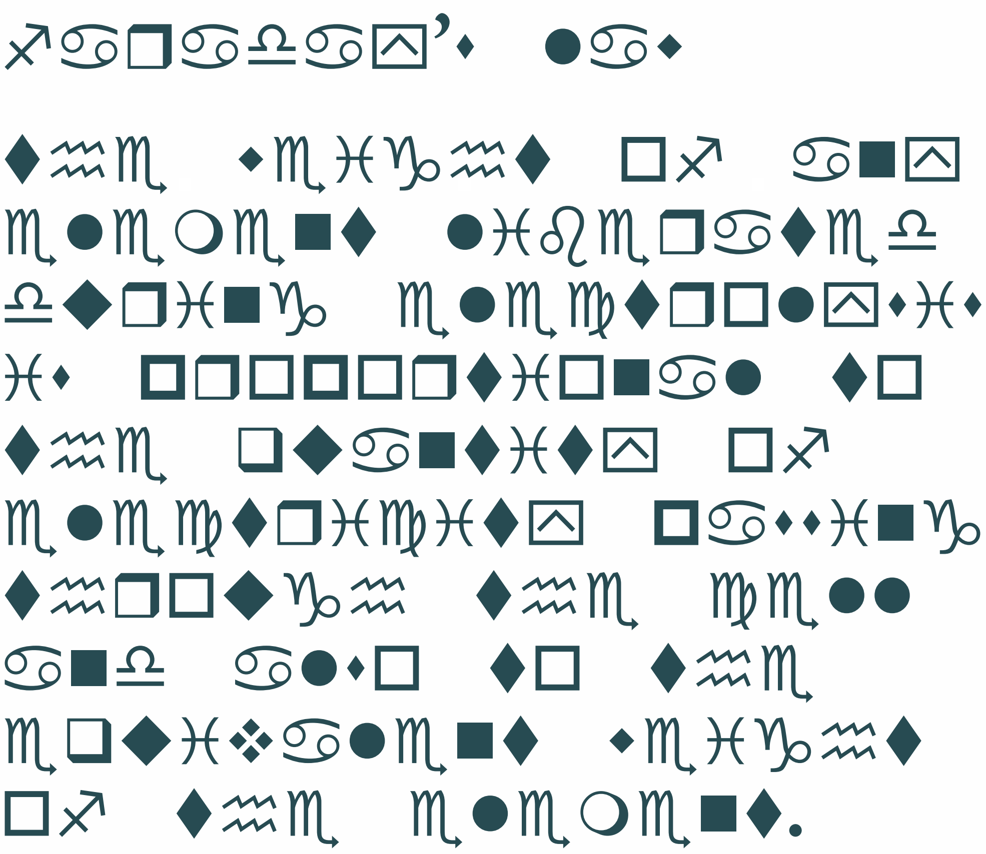
LIGHT AND DARK

A celebrity appearance this issue as Alan Duffy – astrophysicist, SABRE member and author of last issue's Science of Sci-fi cover story took the magazine into the genius lair under construction beneath Stawell (see page 30) for this pic. We'd love to see where you're reading! Please send us a shot of your special science place: **contribute@cosmosmagazine.com**.

GUESS WHO?

QUESTION

Whose Law? Decode where L = ●



HINT:

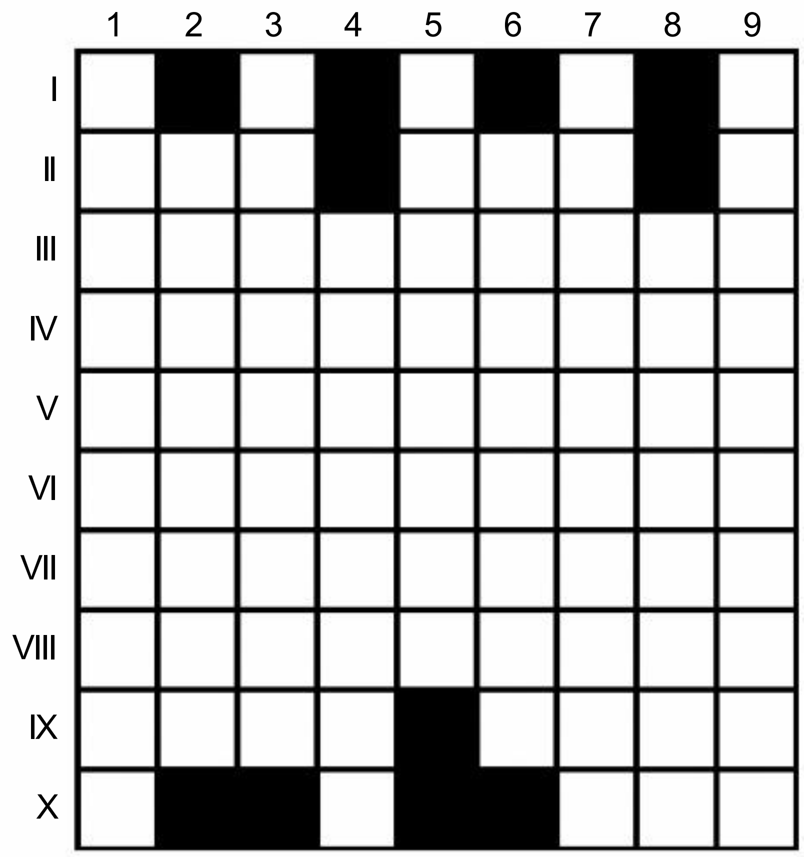
He was an English scientist working in the field of electromagnetism.

MIND GAMES

Who Said?

NO.20

"Science is fun. Science is curiosity. We all have natural curiosity. Science is a process of investigating. It's posing questions and coming up with a method. It's delving in." (5,4)



INSTRUCTIONS

Answers to each of the clues in columns 1 to 9.
Row VII reveals the answer.

CLUES AND COLUMNS

1 Which branch of biology applies the theories and methods of physics to understanding biological systems? (10)
2 What is 10 to the power of -9 of one joule per second? (8)
3 From a word meaning 'small shield', what is the small plate-like dorsal sclerite in an insect's thoracic segments? (9)
4 Which international marker occurs at the meridian of 180 degrees from Greenwich and is adapted so that it does not cut through a landmass? (4,4)
5 What is the scientific name for when the generic and the specific name are the same, as in *Chloris chloris* (the greenfinch)? (8)
6 What is the band of colour produced when white light passes through a prism? (8)
7 In 1785, who invented the power loom? (10)
8 With its name originating from the Latin for 'rising from the marshes', what is the state of having the symptoms of malaria, such as a high fever and chills? (8)
9 Born in Syracuse, Sicily, which Greek mathematician invented a screw for raising water? (10)

Cosmos Codeword

NO.20

4	16	5	11	15	17	13 T	19	■	10	12	19	19	22	19
18	■	4	■	■	■	7	■	20	■	11	■	8	■	15
4	2	2 F	15	17	19	18	26	19	■	4	6	20	15	19
15	■	19	■	5	■	26	■	19	■	24	■	15	■	23
21	11	14	12	17	24	13	■	24	4	25	7	4	13	19
13	■	17	■	4	■	17	■	15	■	5	■	7	■	18
7	■	4	15	15	19	24	14	19	18	■	14	18	4	13
26 C	■	24	■	■	■	19	■	5	■	20	■	■	■	12
■	7	25	7	11	6	■	4	5	20	7	24	7	18	■
5	■	■	■	26	■	4	■	■	■	9	■	11	■	2
1	19	24	4	13	7	18	■	3	11	17	24	18	4	15
19	■	■	■	4	■	5	■	4	■	4	■	7	■	21
10	24	11	18	14	■	10	7	25	19	18	■	26	12	7
19	■	2	■	11	■	19	■	19	■	26	■	■	■	18
24	19	2	7	18	19	24	21	■	26	21	16	11	24	14

1	2	3	4	5	6	7	8	9	10	11	12	13
14	15	16	17	18	19	20	21	22	23	24	25	26

Codeword requires inspired guesswork. It is a crossword without clues. Each letter of the alphabet is used and each letter has its own number. For example, 'A' might be 6 and 'G' might be 23.

Through your knowledge of the English language you will be able to break the code. We have given you three letters to get you started.

ALL PUZZLES DESIGNED AND COMPILED BY SNODGER.COM.AU

It Figures

NO.20

	1	2	3	4
A				
B				
C				
D				

INSTRUCTIONS

Using the clues below place the numbers 1 to 16 correctly in the grid. How many clues do you need?

LEVEL 1 – CHIEF SCIENTIST

1. The digits of the first three numbers in each row create square numbers.
2. The two largest numbers are at opposite ends of the first column.
3. The sum of the first two numbers in Columns 3 and 4 is one less than the third number in each of those columns.
4. The three smallest numbers share a row above the one ending with a 10.
5. The product of the first two numbers in Row B is 56.

LEVEL 2 – SENIOR ANALYST

6. There is a prime number at the beginning or end of every row.
7. The sum of the outer two numbers in Row C is 25.

LEVEL 3 – LAB ASSISTANT

8. The product of the first three numbers in Column 2 is 80.

SOLUTIONS: COSMOS 93

CODEWORD

B	I	N	A	U	R	A	L	■	K	I	D	N	E	Y
O	■	O	■	N	■	C	■	F	■	N	■	E	■	E
T	O	R	P	E	D	O	■	E	Y	E	B	A	L	L
A	■	T	■	N	■	U	■	W	■	X	■	R	■	L
N	I	H	I	L	I	S	T	■	F	I	A	S	C	O
I	■	W	■	I	■	T	■	A	■	S	■	■	■	W
S	E	A	■	G	R	I	N	D	S	T	O	N	E	■
T	■	R	■	H	■	C	■	J	■	E	■	U	■	S
■	E	D	I	T	S	■	N	E	O	N	A	T	A	L
Z	■	■	■	E	■	I	■	C	■	T	■	R	■	I
E	Q	U	A	N	I	M	I	T	Y	■	L	I	M	P
N	■	L	■	E	■	P	■	I	■	A	■	T	■	K
I	O	N	■	D	W	A	R	V	E	S	■	I	N	N
T	■	A	■	■	■	I	■	E	■	I	■	O	■	O
H	A	R	D	W	A	R	E	■	G	A	R	N	E	T

1 W	2 S	3 M	4 Y	5 P	6 C	7 D	8 O	9 B	10 V	11 N	12 X	13 A
14 Q	15 G	16 U	17 R	18 T	19 L	20 E	21 Z	22 K	23 H	24 I	25 J	26 F

IT FIGURES

12	1	10	9
2	15	4	16
5	8	3	13
11	14	6	7

WHO SAID?

John Ruskin

An English writer, philosopher, art critic and polymath, Ruskin wrote on subjects as varied as geology, architecture, myth, ornithology, literature, education, botany and political economy.

WHOSE PRINCIPLE?

ANSWER:

The net mass convergence into a given column of air must be balanced by a net mass divergence from the same column of air.

Dines' compensation

Grace Lawrence

ASTROPHYSICIST

COURTESY OF GRACE LAWRENCE

Grace Lawrence has always gunned for what she wants. As a teenager, she took her twin obsessions seriously. She competed in ballet competitions at a national and regional level, and she became fascinated by physics when a passionate teacher designed a bespoke two-year astrophysics course.

"From about fourteen years old, I knew I wanted to be an astrophysicist. From that time onwards I was absolutely hooked – it had to be physics, and it had to be astrophysics."

While she was still in the first year of an undergraduate science degree, Lawrence signed up to a summer project working on the Sodium-Iodide with Active Background Rejection (SABRE) program, a joint international collaboration between two labs in Australia and Italy that are hunting for theorised particles of dark matter deep underground. That's where she got her introduction to the weird and wonderful world of dark stuff – and what the Cosmos newsroom likes to call the 'genius lair'.

"I just fell in love with dark matter," she says. "What's more alluring than helping to discover 25% of our entire universe? I got to discover what this incredible SABRE experiment was and I was thinking, *my goodness, we're searching space from underground – how quirky and cool is that?*"

Now about to start the final year of her PhD, Lawrence is using high resolution simulations of milky-way type galaxies to model how dark matter is distributed through them. She uses these models to try to make predictions for detectors like SABRE, to help them hunt for the mysterious, intangible matter.

> **"I was thinking, *my goodness, we're searching space from underground – how quirky and cool is that?*"**

Where will she be in ten years' time? Still in the dark part of the universe, if she can help it.

"I'd love to still be actively researching dark matter, whether that's still working on trying to detect it, or perhaps we found it and we're getting to do some really fun science with dark matter. I'd love to continue to research the dark sector of the universe."

READ ABOUT THE GENIUS LAIR AND ITS HUNT FOR DARK MATTER ON PAGE 30.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