Issue 72

THE SCIENCE OF EVERYTHING

Dec—Jan 2017

# COSMOS

WIN
A whale shark adventure swim

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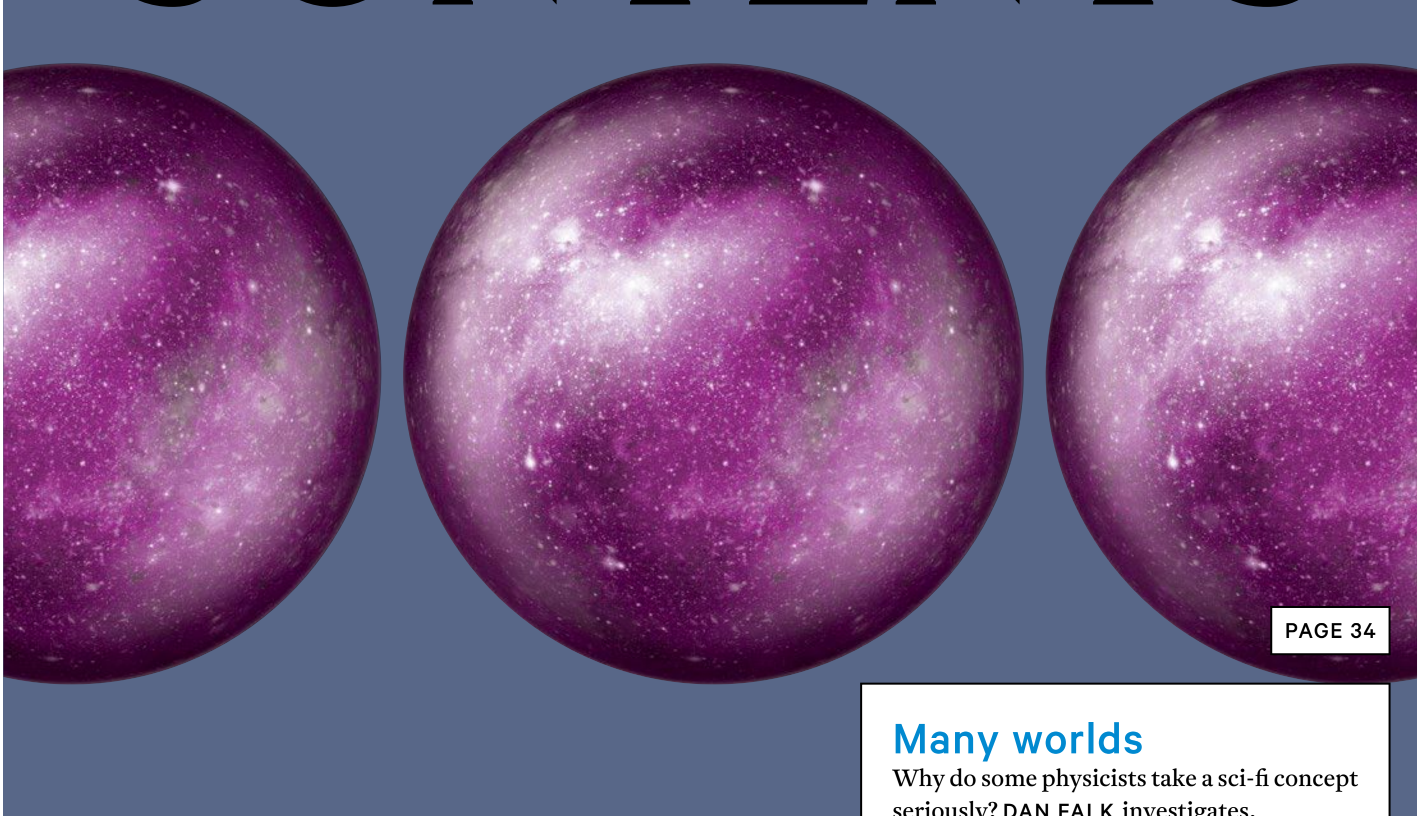

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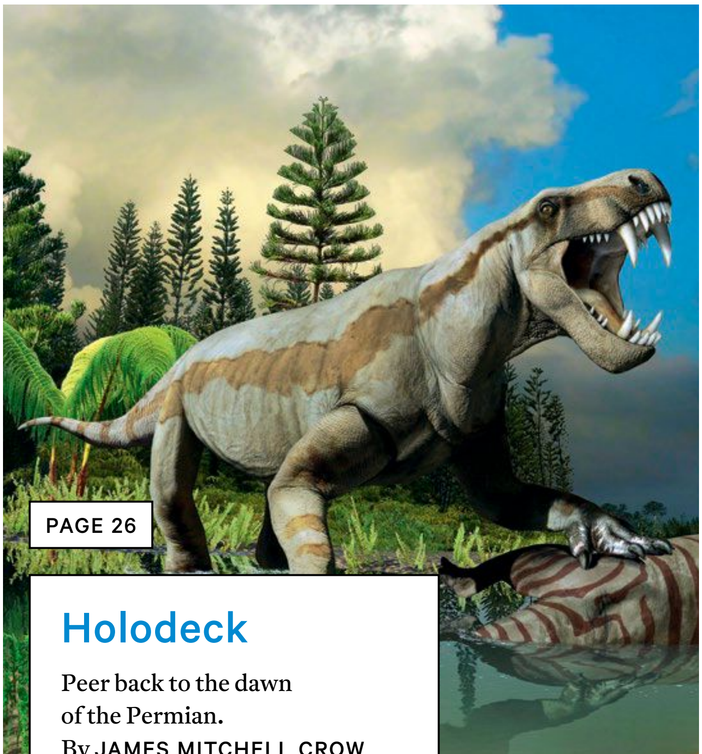

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## Holodeck

Peer back to the dawn of the Permian.
By JAMES MITCHELL CROW

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# FEEDBACK

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Letters to the editor must include the writer's full name, address and daytime telephone number. They may be edited for clarity and length. Please do not send attachments.

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## STEPPING OVER THE LINE ON GENE EDITING

Although I agree with Julian Savulescu (*Cosmos*, Issue 70), that in principle we shouldn't ban all human embryo editing or research outright, most of his arguments, such as his "Genetic Short Straws" and "Human Enhancement", are flawed and overly simplistic to a dangerous degree. I don't think anyone would oppose using gene editing to prevent suffering. However, what constitutes someone who has been dealt a "genetic short straw"?

Even more concerning is Savulescu's references to "moral fitness" and how this is linked to our genes. His argument smacks of a reductionist view of human beings as essentially consisting of their genes. This ideology minimises the importance of social context.

I'm especially concerned by his reference to deviant behaviour and gene editing in the embryo. What would be considered "deviant behaviour"? Remember, for example, homosexuality was considered to be a psychological condition until 1970s.

Savulescu's underlying argument seems to be if you remove the "bad genes" that make us immoral or violent this will help solve all of our problems. There are no simple answers. Despite Savulescu's attempts to convince everyone otherwise, fixing society's problems will be a lot more complicated.

— AMY REES
Bayswater, WA

Julian Savulescu makes some compelling points for genetically engineering babies to eliminate diseases but then lapses into authoritarian and unscientific arguments for rescuing those who have drawn the "short genetic straw" and those who hold right wing views or have antisocial tendencies.

Even if this were to be supported by more research, he ignores the inevitable production of a genetic elite who can afford the right genes for their offspring. Savulescu slides even more into dubious grounds by telling us it is a "moral imperative" to rush into this pathway rather than debate the consequences.

Maybe we should genetically eliminate naive authoritarian eugenicists from our germ-lines to stop the master race from emerging.

— CARMELO AQUILINA
Leichhardt, NSW

## PUN INTENDED?

In a recent article, "Young Frankenstein" (*Cosmos*, Issue 69) on the potential role of electricity in the regeneration of body parts, the author observes that, even if they have some success with mice, "there's no guarantee that they'll be able to replicate the feat in humans".

Boom boom.

— WAYNE HOSKING
Geraldton, WA

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# EDITOR'S NOTE

ELIZABETH FINKEL
Editor-in-chief

## What is *Cosmos* doing sporting a cover story on parallel universes?

CARL SAGAN ONCE admonished that extraordinary claims require extraordinary evidence. We're certainly not claiming to present such evidence, but our cover story does address why some physicists consider that this darling of science fiction is nevertheless a respectable theory in science. They argue that Sagan's admonishment has been met, in a way, because the hypothesis for other worlds emerged from the extraordinary evidence of the quantum world.

In our world, waves are waves and particles are particles. But in the sub-atomic quantum world, there's no such distinction. That reality is dramatically illustrated by experiments that show electrons – particles of matter – interfere with each other just as they would if they were two ocean waves. Weirdest of all, a solitary electron can behave as if it existed in two places at the same time.

Physicists have never figured out what this means. Nevertheless, by 1926 they were able to mathematically describe the behaviour with a "wave function". It has no precise position or speed until the moment you "detect" it and then it suddenly manifests as a particle.

However, from time to time, people have tried to understand what quantum mechanics says about reality. In 1953, Hugh Everett, a PhD student at Princeton University, had a flash of intuition. The weirdness of the quantum world could be explained by invoking the existence of other worlds. The moment you "detect" an electron, its probability wave splits into multiple worlds. In this world, you perceive it doing one thing but in another, a different you perceives it doing something different, in a way that has inspired any number of science fiction plots. But the "Many Worlds" concept, especially its recent articulation by Griffith University physicists Michael Hall and Howard Wiseman, does explain how a single electron might "interfere" with itself – it's experiencing the effects of electrons from another world.

So is explaining something weird by proposing something weird a respectable way to approach physics? That remains hugely debated. On one hand, physics throws up weird stuff all the time – typically when maths is deployed to discern an underlying pattern in data. It was from the scrawl of Einstein's general relativity equations that empty space was revealed as a fabric that could be dimpled by matter. But Einstein's bizarre theory had a winning feature: it was testable. Physicists can't really test for the existence of many worlds. But they can test to see if such models work to describe the quantum world, at least as well as the idea of a probability wave.

Weird and befuddling isn't it? Take comfort in Richard Feynman's adage: "I think I can safely say that nobody understands quantum mechanics." And he was one of the greatest quantum physicists of the late 20th century. Perhaps it's a matter of replacing one wacky idea with another. In this weird quantum world, may the best hypothesis win!

ISSUE 72


COVER
Absurd and intriguing: we explain how parallel universes became part of the scientific narrative.
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"MATH. IT'S JUST THERE ... YOU'RE EITHER RIGHT OR YOU'RE WRONG. THAT'S WHAT I LIKE ABOUT IT."
— KATHERINE JOHNSON (1918)
NASA RESEARCH MATHEMATICIAN

CREDIT: NASA

A CLOSER LOOK AT THE BIG STORIES

# DIGEST

LIFE SCIENCES

## Settling the debate over the origins of Australian Aboriginals

**The largest study of their genome shows they are one big family. ELIZABETH FINKEL reports.**

The peopling of Australia has long raised questions. Archaeological evidence shows the first arrivals set foot here more than 50,000 years ago. But what happened next has left archaeologists guessing for years. The archaeological record shows huge diversity in the appearance of ancient skeletons and sudden transitions in stone tool technology and art styles. →

Unusual styles of rock art like these Bradshaws from the Kimberley are home-grown, not imported.

CREDIT: M. GEBICKI / GETTY IMAGES

→ Is that evidence of multiple waves of migration, or of a single group evolving in response to a challenging environment?

Now the first major study of the DNA of 83 Australian Aborigines appears to settle the argument. "The genetic evidence shows Australia was only peopled once," says anthropologist Darren Curnoe at the University of New South Wales.

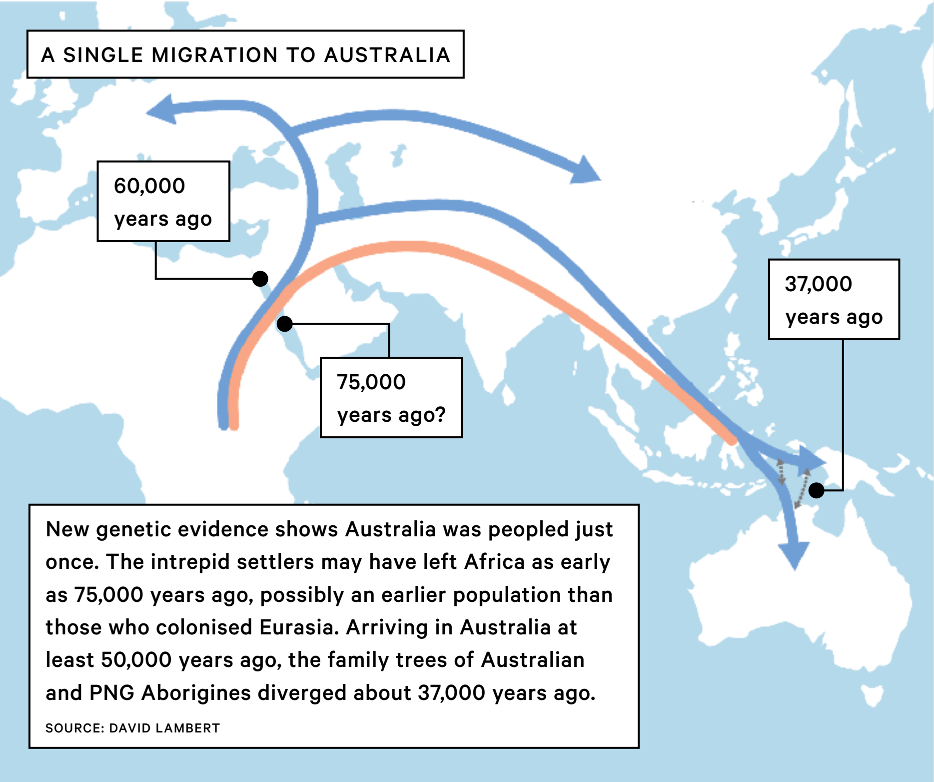
The study, published in *Nature* in September, was led by David Lambert at the Australian Research Centre of Human Evolution at Griffith University in Queensland and Eske Willerslev at the Natural History Museum of Denmark, in collaboration with 76 international colleagues, including Aboriginal elders.

Until now, genetic studies to trace the origins of Australian Aboriginals provided an incomplete picture by analysing sections of the Y chromosome or mitochondrial DNA. While they generally hinted at a single origin, one study did suggest a later arrival of East Indians. To get the full picture requires reading every one of the six billion letters of the human genome – a much more expensive and technically demanding exercise. Before this study, only three full genomes had been read.

The current project originated with a request from Aboriginal elders at Cape York in northern Australia who wanted to know if an ancient skeleton was kin. They approached researchers at Griffith University who had a collaboration with Willerslev, an expert on ancient human DNA. Ultimately, the project expanded to address the origins of modern Aboriginal Australians.

The researchers reconstructed genetic family trees by tracing variations in the DNA code. They showed that Australian Aborigines represent one big family and are most closely related to people from the Papua New Guinea highlands, 25 of whom were included in the study. The analysis showed the family trees split 37,000 years ago, even though the two landmasses remained connected until about 10,000 years ago.

The group's common ancestors were among the first modern humans to leave Africa, journeying across the Middle East and Asia, crossing the sea between the islands of the Indonesian archipelago,




New genetic evidence shows Australia was peopled just once. The intrepid settlers may have left Africa as early as 75,000 years ago, possibly an earlier population than those who colonised Eurasia. Arriving in Australia at least 50,000 years ago, the family trees of Australian and PNG Aborigines diverged about 37,000 years ago.

SOURCE: DAVID LAMBERT

and then perhaps casting off from Timor into the deep blue to arrive at the fringes of Sahul – the combined Australia-New Guinea landmass.

So was this wave of migration out of Africa the same one that populated Eurasia?

To find out, two other papers published in the same issue of *Nature* explored ancestral relationships between diverse populations in Eurasia, Australia and New Guinea. They came to different conclusions – possibly because they each had access to a very small and different set of Australian Aboriginal genomes.

'THE GENETIC EVIDENCE SHOWS AUSTRALIA WAS ONLY PEOPLED ONCE.'

One of the papers, whose lead authors include Harvard's David Reich and The Max Planck Institute's Svante Paabo, suggests a single group left Africa about 60,000 years ago and then parted ways to found the populations of Eurasia and Sahul. Their study, known as the Simons Genome Diversity Project, was based on data from 142 populations.

The other paper, led by researchers at the Estonian Biocentre and Willerslev, compared the DNA of 148 populations. They concluded that Sahul's founders probably left Africa in an earlier wave, about 75,000 years ago.

That interpretation would help explain why, of any modern population, Papuans and Australian Aboriginals have the highest percentage of Neanderthal and Denisovan DNA, even though these archaic humans, who lived in Asia and Europe, never made it to Sahul. If the ancestors of Aborigines and Papuans left Africa earlier, the timing would have been better to encounter these groups.

Another controversy relates to how the Aboriginal language group known as Pama Nyungan came to dominate Australia about 6,000 years ago. Lambert and Willerslev say the DNA tells the tale. Tracing DNA signatures, they find a small population from the northeast dispersed to other parts of the country about 10,000 years ago and may have taken the language with them.

Alan Cooper, director of the Australian Centre for Ancient DNA in Adelaide, remains unconvinced by that evidence. "There's still a lot of debate," he says.

LIFE SCIENCES

# Bananas at risk from killer fungi

**Genetic discoveries could spur new ways to fight the pathogens, ESTHER LANDHUIS reports.**

It's hard to imagine a world without bananas, but a trio of parasitic fungi threatens to make that vision all too real. New genetic research is unpeeling the mystery of how these pathogens operate – and could lead to more effective strategies for saving the staple fruit.

The fungi cause black Sigatoka and related diseases in banana-growing regions of Australia and other countries. The pathogens spread by releasing airborne spores that attack the leaves of banana plants, leeching nutrients as they destroy plant tissue. The first signs of trouble are small, yellow spots, which then grow into dark streaks. As photosynthesis slows, so does the plant's banana yield. In severe cases, infected plants produce only half as much fruit.

Farmers can reduce their losses with fungicides, but the sprays are expensive and have become increasingly ineffective as pathogens develop resistance. "You have to spray even more," says Gert Kema, a plant pathologist at Wageningen University in the Netherlands. "It's a vicious cycle."

In regions where bananas are an essential part of the local diet, the losses could be devastating. In Uganda, for instance, the average person consumes half a kilogram per day – about five to six bananas, says James Dale, a biotechnologist at Queensland University of Technology.

By probing the pathogens' genetic underpinnings, researchers are beginning to learn what makes them such formidable foes – the first step to outsmarting them. In a study published in August in *PLOS Genetics*, Kema and his colleagues sequenced the genomes of the culprit fungi and pinpointed key genes that help the pathogens launch their attack. A second study in the same journal revealed another key insight: how the genomes of some fungi have evolved to allow the pathogens to siphon more nutrients from their banana host. By knowing which genes the fungi target, researchers could potentially alter them and develop disease-resistant bananas.

Researchers tend to focus on the host crop, Kema says, but "if you look at the problem from both sides – host and pathogen – you can make big leaps".

To analyse the genome of the black Sigatoka fungus, *Mycosphaerella fijiensis*, Kema's team combed through 74 million base pairs, looking for stretches that encode proteins called effectors. Fungi secrete these effectors onto the host plant. If unchecked, the fungi will start stealing the plant's nutrients, slowing photosynthesis. But some plants can mount a chemical defence: resistance genes order the production of plant proteins that function like antibodies in an animal's immune system.

Kema and his colleagues found a gene in black Sigatoka fungus that resembles a known effector gene, called *Avr4*, from a different fungus that preys on tomato plants. Typically, if plant hosts have resistance genes against a particular effector, they will put up a fight. To check for this defence response, the researchers injected the *Avr4* effector into the plant and looked for a chemical reaction that produces a brown smudge on the leaves.

The researchers expected a banana plant that resists black Sigatoka to show signs of fighting back – the tell-tale brown smudge – and a plant that's susceptible to black Sigatoka to produce no evidence of this defence. And this is what they saw.

When the researchers injected Avr4 protein into the leaves of Cavendish banana plants, which make the most popular export banana and are known to succumb to Sigatoka diseases, they saw no brown smudge.

But when they did the same experiment with wild bananas that are naturally resistant to Sigatoka, the leaves turned brown. That suggests wild bananas' defence against black Sigatoka comes from a resistance protein that recognises the pathogen's *Avr4*-like effector. It should be possible to transfer the gene that encodes that resistance protein into Cavendish and other susceptible bananas so they too can resist Sigatoka fungi, Kema says.

But let's say the invasive fungi get past a banana plant's initial line of defence – its immune-like resistance. Could there be a way to keep them from gaining a foothold? The second *PLOS Genetics* paper offers some clues. Researchers at the University of California, Davis compared the genomes of the black Sigatoka fungus to the genomes of two related strains that cause somewhat milder banana leaf diseases: yellow Sigatoka and eumusae leaf spot. Among the three fungi, black Sigatoka and eumusae fungi pose the greatest threats.

IT SHOULD BE POSSIBLE TO TRANSFER THE GENE THAT ENCODES THAT RESISTANCE PROTEIN INTO CAVENDISH AND OTHER SUSCEPTIBLE BANANAS.

The researchers scrutinised the fungal genomes, looking for patterns of gene changes over time. They noted which changes were shared by the two stronger pathogens. The team found parallel changes in genes that control metabolism – in particular, those that help fungi break down cell walls and extract nourishment from plant cells.

The findings suggest that black Sigatoka and eumusae fungi "evolved a more aggressive way to get nutrients from the host", says computational biologist and lead author Ti-Cheng Chang. Chang conducted the research at UC Davis and now works at St. Jude Children's Research Hospital in Tennessee.

The next step, Chang says, is to figure out how to use this information to bolster banana plants' defences. Since the DNA changes occurred in fungal genes that control metabolism, he and his colleagues think they might be able to go into the banana and tweak the metabolic pathways the fungi use to thwart the pathogen's attack.

SPACE

# Goodbye Rosetta

**During its lifetime, the comet chaser transformed our understanding of the solar system – but its afterlife may have much to teach us too.
RICHARD A. LOVETT reports.**

When the European Space Agency's Rosetta spacecraft was launched in March 2004, nobody expected it to end its 12-year sojourn by falling gently to the surface of a comet, like an autumn leaf. With its solar panels giving it a wingspan of 32 metres, one thing it was never intended to be was a lander, even in the incredibly low gravity of a comet. Rather, its mission was simply to rendezvous with a comet called 67P/Churyumov-Gerasimenko and shadow it as it dived close to the sun, observing the changes that occurred as the comet warmed.

But as the mission drew to a close, the scientists decided to go out with a gentle crunch. On 30 September, the spacecraft ended its mission in a slow-motion crash, snapping increasingly detailed images as it drew ever closer to its demise. By the end, said Holger Sierks, principal investigator for Rosetta's main camera, these "super-duper" images were so close-up that resolutions were down to millimetre level. "This the first time the comet has been imaged at this resolution," he said, when the spacecraft was still more than a kilometre above the surface.

It was a suitable finale to a mission that has been rich in drama since the beginning.

En route to the comet, the three-tonne spacecraft bounced through the inner solar system like an interplanetary pinball, gaining gravitational kicks from three close encounters with Earth and one with Mars. It flew by two asteroids and spent nearly three years in hibernation mode when its trajectory carried it so far out from the sun that its solar panels couldn't provide enough power to keep its computer fully functional.

When it reawakened, the spacecraft braked into orbit around the comet, mapped the surface for a couple months and deployed a lander to take detailed measurements of the surface. But things didn't go quite as planned. The lander was supposed to affix itself to its landing site by firing a pair of "harpoons" designed to hold it in place in the comet's miniscule gravity. Instead, it bounced. And bounced.

As Paul Weissman, a planetary scientist at the Planetary Sciences Institute, Tucson, Arizona, later joked, it didn't just make the first-ever landing on a comet – "it landed three times". When it finally came to rest, it was in the shadow of a cliff where its solar panels couldn't get enough power to complete all of the intended tests (though it was able to finish many during the two-and-a-half days before its batteries failed).

But the science was even more dramatic than the landing.

Rosetta draws its name from the Rosetta Stone, a tombstone-sized slab of granite whose inscription allowed archaeologists to translate Egyptian hieroglyphs – opening a vast new realm of historical understanding. The name fits: comets are widely believed to be remnants of the early solar system that have spent billions of years deep-frozen in its cold outer reaches. Then some random tug of gravity sends them plunging inward for us to observe.

Artist's impression of Rosetta shortly before hitting Comet 67P/Churyumov–Gerasimenko on 30 September 2016.

CREDIT: ESA / ATG MEDIALAB

"We're pretty certain that we really are looking back at the formation period of the solar system," says Bonnie Buratti, a planetary scientist from NASA's Jet Propulsion Laboratory in Pasadena, California, who was part of the Rosetta team.

One goal was to test a theory that Earth's water was brought to us by a "rain of comets" late in our planet's formation. Rosetta's instruments measured isotope ratios in water escaping from the comet for comparison to those in Earth's oceans. The water didn't match. That meant our water must have come from elsewhere, possibly different types of comets, or from ice-containing asteroids.

THE SPACECRAFT DEPLOYED A LANDER. BUT THINGS DIDN'T GO QUITE AS PLANNED.

Another find was that the comet's surface is peppered with pits whose cliff-like walls offer a glimpse into the subsurface, just as roadcuts and cliff faces do on Earth. Intriguingly, these walls were studded with boulders, one to three metres in diameter.

Nicknamed "dinosaur eggs", these boulders offer clues to how the comet was formed – that may also apply to the origin of protoplanets that later coalesced into planets. They lend support to what is called the pebble-accretion model, in which protoplanets are formed not from cascading collisions of ever-larger pieces, but from large numbers of primordial "pebbles" that somehow come together in comet-sized agglomerations.

Before this mission, adds Buratti, "our idea of how the solar system formed the planets was very shadowy. There was dust, and then miraculously planetesimals formed. [Now] you can find the progression of how these were put together".

When the decision was made to end Rosetta's mission with a crash landing, one of the goals was to make sure its final

**Snapping photos until the last moment, Rosetta captured this wide-angle shot of comet 67P at a distance of 22.9 kilometres.**

CREDIT: ESA / ROSETTA / MPS FOR OSIRIS TEAM MPS / UPD / LAM / IAA / SSO / INTA / UPM / DASP / IDA

trajectory provided the best-ever views of these boulders.

And there really wasn't that much to lose by ending the mission this way, says project scientist Matt Taylor. The comet was rapidly receding from the sun, carrying the spacecraft with it. Already there wasn't enough power to keep all of its instruments running and the data transmission rate had dropped by 90%. The only other option would have been to put the spacecraft back into hibernation mode and hope it could be revived again years from now as it drew back towards the sun on the comet's next close approach. It was a classic bird-in-hand choice. "This was the option where we'd maximise the science," Taylor says.

But while Rosetta has finally come to rest, the mission is far from over. "We've analysed only like 5% of the data," says Art Chmielewski, Rosetta's US project manager. And to date, he adds, scientists have been looking only at data from their own instruments. Now they'll be coming together in groups to share information. "There's years of hard work ahead," he says.

Taylor agrees. "The spacecraft may end, but the science will continue."

LIFE SCIENCES

## Alzheimer's research: a tentative new hope

After years of failure, finally a treatment that seems to slow Alzheimer's disease. ELIZABETH FINKEL reports.

Alzheimer's researchers have taken a beating over the past decade, as drug after drug has failed to halt patients' mental decline. Worse, the failures seemed to suggest their major theory for what causes Alzheimer's disease – clumps of a protein called beta-amyloid accumulating in the brain – must itself be wrong.

Now it seems rumours of the death of the "amyloid hypothesis" were exaggerated.

For a year, researchers gave 165 people with early-stage Alzheimer's disease monthly injections of either a placebo or an amyloid-targeting antibody called aducanumab. Though the study was small and preliminary, the new therapy made a significant dent in deposits of beta-amyloid, especially in people who received higher doses. For patients in the highest-dose group, the drug removed the bulk of the deposits. It also appeared to slow mental decline – again, especially for patients who received the highest doses.

The trial, conducted by the Cambridge, Massachusetts company Biogen, was detailed in *Nature* in September and has already been met with a mixed reaction.

"It's a great result; in a small subset, the results are so convincing," says neuroscientist Colin Masters at the University of Melbourne. Others wonder whether the positive results could be a statistical glitch and are reserving judgement until larger trials are completed.

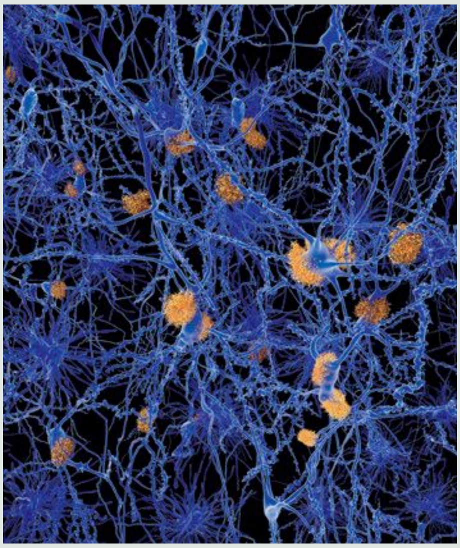
"While the clinical results have generated exceptional enthusiasm, they must be interpreted with caution," says Bryce Vissel, a neuroscientist from Sydney's Garvan Institute.

Still, the big question is why this drug shows any success at all, when previous drugs that also targeted amyloid deposits failed to slow patients' mental decline.

Two potential reasons, says Masters.

The first involves the way patients were selected for the trial. In previous studies, "a third of patients probably did not even have Alzheimer's disease", he says. Until now, patients were selected based on their scores on mental ability tests, which could not separate Alzheimer's cases from people with mini-strokes or other neurodegenerative diseases. The current trial was the first to use a new PET brain scan technique to confirm that prospective participants actually carried amyloid clumps.

The second reason for the trial's success may be the drug itself. Beta-amyloid levels build up in people as they age, yet some people never develop the gluggy deposits. Scientists from Swiss



At last: researchers finally have evidence that getting rid of these brain protein clumps, can help Alzheimer's patients.

CREDIT: SELVANEGRA / GETTY IMAGES

LIFE SCIENCES

## Microscopic X-Men

Tardigrades share the secret of their radiation resistance. ANTHEA BATSAKIS reports.

Don't let their cuddly bodies fool you – tardigrades are almost impossible to kill.

These microscopic animals need a watery environment to thrive – marine, freshwater or even damp moss will do. But they can survive years of dehydration as well as freezing and boiling. In 2007, they were even blasted into space on a satellite for 12 days, and survived the vacuum and radiation. Now a group of scientists led by Takekazu Kunieda from the University of Tokyo have discovered the secret of the tardigrade's radiation resistance – a gene that armour-plates its DNA. The findings were published in the September issue of *Nature Communications*.

Of some 1,000 species of tardigrades, the team zeroed in on one of the most radiation-tolerant species, *Ramazzottius varieornatus*: it can withstand a dose of radiation 1,000 times higher than that of a human being. The team read its DNA sequence and identified a gene responsible for radiation resistance. It was aptly named "Damage suppressor" or *Dsup* for short.

To find out if this superpower was transferrable, they spliced the gene into the DNA of human cells growing on a dish. It curbed X-ray radiation damage by 40%.

*DSUP* IS A GENE THAT ARMOUR-PLATES TARDIGRADE DNA.

Kunieda hopes that understanding how *Dsup* works will provide strategies for finding drugs that act in a similar way – and protect cancer patients from the harms of radiation therapy.

"Many questions remain, but this study has opened up new potential pathways," says Michal Schneider, a radiologist at Monash University in Melbourne.

company Neurimmune wondered if that was because those people were naturally producing antibodies to clear the gunk away. To test their idea, they analysed the blood of 1,000 elderly people who did not have dementia, searching for cells that make antibodies against beta-amyloid. Their search yielded aducanumab.

Antibodies used in previous clinical trials were produced in mice by injecting them with beta-amyloid fragments, then waiting for the animals to mount an immune response. Parts of the mouse antibody were then re-engineered to "humanise" them. But aducanumab has different properties to the mouse-made antibodies. For one thing, it does not recognise single units of the protein, only aggregates. And it has already been road-tested in a human – presumably protecting the person who made it from developing the disease.

Whether or not aducanumab can help others fight the disease, as the current trial suggests, will have to await confirmation in a follow-up trial. The current trial, known as a phase 1b, was only designed to test whether the drug could clear the deposits, and to find a safe dose. The patients who received the highest dose showed the greatest slowing of the disease, but also the highest rate of a side effect dubbed ARIA – a slight swelling of the brain. The side effect was higher in patents who carried a gene called *APOE4*, which increases the risk of Alzheimer's.

The next trial – a phase 3 – will involve thousands of patients and will measure how effectively the drug slows the disease, as well its potential side effects.

Nevertheless, the current finding is "still an exciting result", says Ashley Bush, a neuroscientist at Melbourne's Florey Institute. "It shows beta-amyloid is part of the story."

The story is thought to be a long one: by the time a person begins to show the first signs of dementia, beta-amyloid may have been accruing in the brain for 20 years.

Many researchers think the best treatment strategy, then, may be to prevent the protein build-up in the first place. "This [current] trial encourages us to believe it's worth testing amyloid-clearing drugs in people who don't have symptoms," Bush says.

She and Masters are part of a study that will test that idea. They are enrolling 100 cognitively normal people aged 65-85 for the "A4 study" funded by Eli Lilly. Globally, 1,000 people are being enrolled. Following a PET scan, those with the first signs of elevated beta-amyloid levels will be randomly assigned to receive a placebo or an antibody that clears amyloid – potentially halting the disease before it has even begun.

Tardigrades can survive a radiation hit 1,000 times higher than the lethal dose for a human. Researchers have just identified the responsible gene. CREDIT: EYE OF SCIENCE / GETTY IMAGES

BY THE NUMBERS

# NOT JUST ONE SPECIES

## 100,000

Number of giraffes left in the wild. Until recently, scientists thought they represented a single species.

## 190

Giraffes from across Africa whose skin samples were used for DNA profiling.

## 4

The revised number of giraffe species, based on those DNA profiles, as published in *Cell Biology* in September. The species are: southern giraffe (*Giraffa giraffa*), Masai giraffe (*G. tippelskirchi*), reticulated giraffe (*G. reticulata*) and northern giraffe (*G. camelopardalis*). Reticulated and northern giraffes are now classified among the most endangered large mammals in the world, with fewer than 4,750 reticulated and 8,700 northern wild individuals.

# TECHNOPHILE

## Can robots keep us safe?

Meet the next generation of security guards.
By CATHAL O'CONNELL.

*ED-209 Enforcement Droid: [menacingly] Please put down your weapon. You have 20 seconds to comply.*

Almost 30 years since *Robocop* hit our screens, robot security guards could be about to transform the security industry. But unlike the gun-toting robots of the movies, these real-life robo-guards are equipped not with weapons but with an arsenal of cameras and security sensors.

The latest to hit the market is Knightscope's 1.5-metre-tall, 136-kilogram K5 security robot. With looks that are half -Dalek, half fridge-freezer, the K5 manages to be simultaneously cute and imposing. Its R2D2-esque little brother, the K3, is smaller and more manoeuvrable for indoor environments. The robots will autonomously patrol a designated circuit and signal an alarm if they detect any suspicious activity.

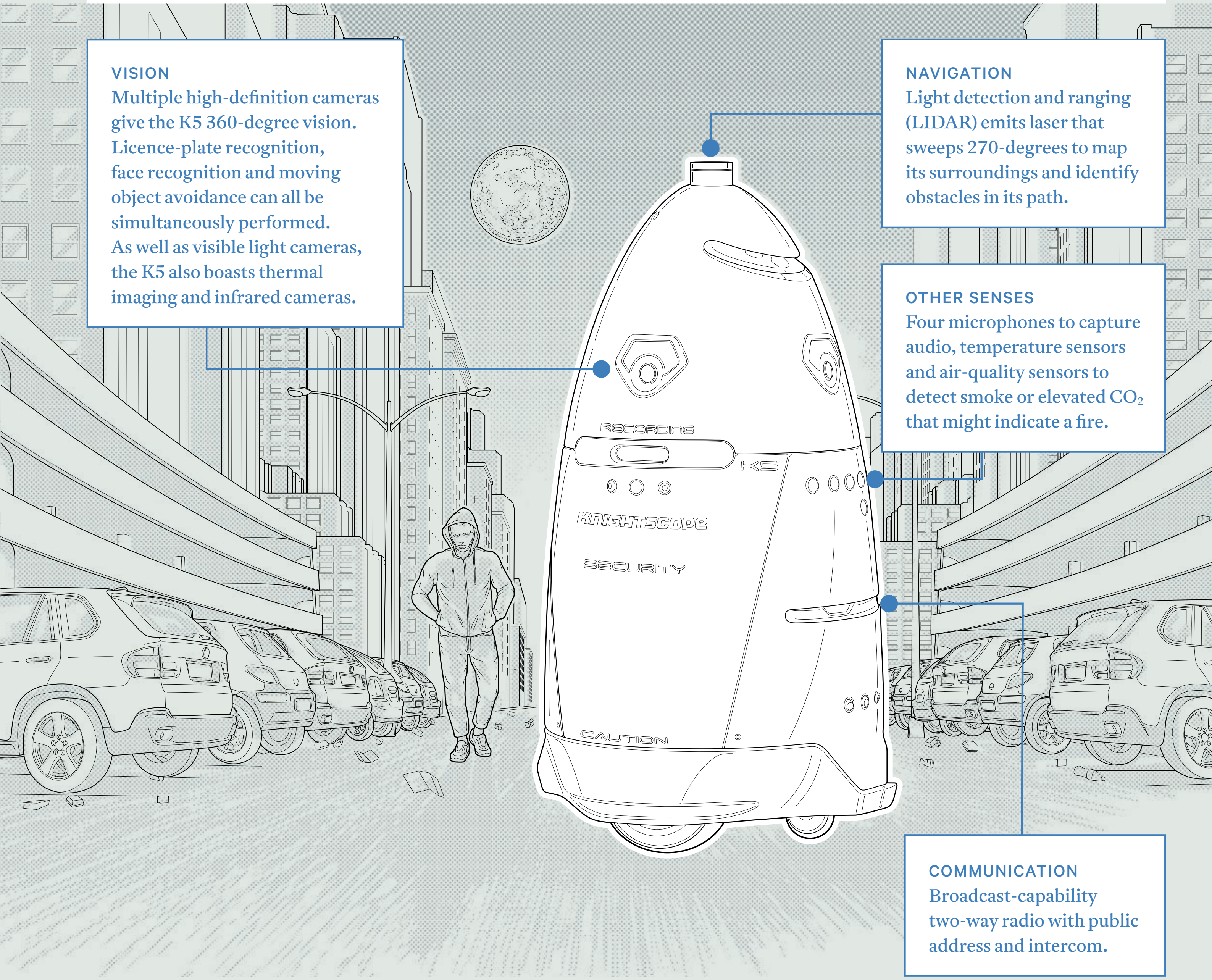
Knightscope isn't the first robotics company to try to muscle in on the security business. "Robot security guards have actually been on offer for a surprisingly long time," says Paul Pounds, a research engineer at the University of Queensland. In the early 2000s, Japanese firm Tmsuk developed a range of robo-guards, including their *Banryu* guard dog. But these early incarnations lacked the smarts to reliably and autonomously patrol a beat, and never made an impact.

The K5, in comparison, navigates just like a driverless car, using LIDAR (light detection and ranging) to bounce laser light off of its surroundings to map out its 3-D environment and avoid obstacles. Mapping software ensures K5 doesn't stray beyond its patrol perimeter. K5, which has been under development for more than three years, has logged more than 35,000 hours of testing, autonomously patrolling shopping centres, car parks and factories across California. The robots have already been sent on patrol at Microsoft and Uber.

The K5 is equipped with so many sensors – almost 30, all told – it amasses security data at a rate of 90 terabytes a year. Its 360-degree vision means it literally has eyes in the back of its head, while its infra-red camera gives it night vision. It can read licence plates (up to 300 per minute) and check them against a blacklisted database. It can recognise faces and, if linked to police records, could constantly scan for faces of wanted criminals. K5 can also call an alarm if it hears a suspiciously large bang, sees a flash or smells smoke.

Knightscope maintains they're not out to put security guards out of work, just to take the drudgery out of the routine patrol beat – leaving strategic decisions to humans in a control room. Without any ability to intervene in a crime, the company bills its robots as "Autonomous Data Machines" – more a smart security

**K5 SPECIFICATIONS**
**HEIGHT:** 1.5 metres
**WEIGHT:** 136 kilograms
**COST:** US$7 an hour to rent (or about $60,000 per year)
**BATTERY LIFE:** Two to three hours, then dock and charge for 20 minutes (though it keeps working through the 'coffee break' period)
**PATROL SPEED:** 2-5 kilometres per hour
**TOP SPEED:** 29 kilometres per hour
**DATA COLLECTION:** 90 terabytes per year




camera on wheels than a security guard.

But the K5's constant video and microphone feed has generated controversy. Jeramie Scott, a national security fellow at the Electronic Privacy Information Centre in Washington, DC, has warned that the K5 "could become like a cuter, less aggressive Terminator that kills privacy instead of people".

Meanwhile K5's agility has also been questioned. On one of its first big jobs patrolling a shopping centre in Palo Alto, K5 collided with a 16-month-old toddler, leaving the boy with a bruised foot – though whether robot ran into child or child ran into robot is a matter of dispute.

Teething issues notwithstanding, the brothers Knightscope are the first in a new generation of robot security guards that might turn the security industry on its head. Colorado-based Gamma 2 Robotics has RAMSEE, a similar style of security robot to K5. Japan's Sharp Corporation has its Autonomous Unmanned Ground Vehicle (A-UGV), a squat, four-wheeled droid that looks a bit like a bomb disposal bot on patrol. And for even more rugged outdoor terrain, there's SMP Robotics' Rover S5, designed for tasks such as patrolling the perimeter fencing of power plants. All three are billed for release in 2017.

But K5's real competition is in the air, says Pounds. "Security drones have the advantage of moving faster, covering more ground, and being out of reach of people on the ground." And unlike ground-based security bots – even Robocop's fictional ED-209 – flying drones won't be stopped by a simple flight of stairs. ©

→ See the K5 in action here: bit.ly/cos72K5

ILLUSTRATION: ANTHONY CALVERT

SPECIAL FEATURE

# NOBEL PRIZES FOR SCIENCE

## Winners round-up

**Strange states of matter, the cell's recycling machinery and molecular machines all inspired the 2016 recipients of science's most prestigious accolade. CATHAL O'CONNELL reports.**

### THE NOBEL PRIZE IN PHYSICS

This year's Nobel Prize in Physics went to three scientists who used the mathematics of topology – a study of shape – to explain the properties of exotic states of matter.

Superfluids, such as liquid helium, form a Bose-Einstein condensate – a kind of atomic groupthink where the atoms behave like one giant atom. This generates zero resistance to flow, or superfluidity.

Give liquid helium a stir, for example, and the whirlpool would spin forever. Coupled with its sensational ability to transfer heat, this flow property makes liquid helium the world's ultimate coolant – used to deep-freeze the 27-kilometre ring of the Large Hadron Collider.

In the 1970s, physicists thought they had the theory of superfluidity wrapped up, but then David Thouless at the University of Washington and Michael Kosterlitz at Brown University realised that miniature whirlpools spinning in opposite directions could link together, like two meshing gears. Tiny temperature rises cause decoupling. That sudden shift in the superfluid's topology brings unexpected changes in its density and coolant properties.

Thouless also used topology to explain the quantum Hall effect, a baffling phenomenon in flat materials where electrical resistance suddenly takes on multiple values of the number 25,812.807557. He realised electrons can gang together and run along the edge of the flat material, a bit like streams of droplets running down a windowpane. Each additional "stream" decreases the resistance by exactly 25,812.807557 ohms.

Meanwhile, Duncan Haldane at Princeton University used topology to predict strange properties in chains of magnets. A chain can have different magnetic properties depending on whether it has an odd or even number of magnets.

The work has led to the creation of strange materials such as topological insulators. Insulators on the inside but conductors on the outside, they could help make more reliable quantum computers.

### THE NOBEL PRIZE IN PHYSIOLOGY OR MEDICINE

Yoshinori Ohsumi at the Tokyo Institute of Technology won the prize for medicine for revealing how cells recycle their contents.

Autophagy, literally "self-eating", refers to the observation that starving cells start breaking down internal organelles for protein – much as a starving person will break down their own muscle tissue.

Aided by an electron microscope, biologists had observed this process in mammalian cells in the 1960s. But Ohsumi wanted to find the genetic controls, so in the 1960s he switched to a cell where gene hunting was easier: baker's yeast.

Starving yeast cells underwent a similar recycling process, packaging up organelles in compartments called vacuoles. Some strains of yeast, especially those treated with mutagenic chemicals, didn't form vacuoles in the normal way. Ohsumi guessed that their autophagy

David Thouless, Duncan Haldane, Michael Kosterlitz, Yoshinori Ohsumi, Jean-Pierre Sauvage, Fraser Stoddart, Bernard Feringa. CREDITS: GETTY genes had been disrupted. His analysis identified 15 "atg" genes crucial to the mechanism. The same genes were shown to be important for autophagy in human cells.

It turns out recycling is not just important for salvaging nutrients; it's also crucial for a cell's hygiene.

When it fails, it can lead to chronic inflammation explaining the link between autophagy and inflammatory diseases such as Crohn's disease. Autophagy has also been linked to cancer and neurological diseases and plays a big clean-up role during the sometimes messy process of embryonic development.

## THE NOBEL PRIZE IN CHEMISTRY

What's the tiniest machine ever made? How about a 1,000th the width of a human hair? This year's Nobel Prize in Chemistry went to three chemists for creating the world's first machines made from individual molecules.

Nature is great at making molecular machines like the motor protein, myosin, which ratchets itself along a fibre to make muscles contract. But to copy nature's feat, chemists had to learn to make molecules with moving parts.

That happened in 1983 when Jean-Pierre Sauvage of Strasbourg University linked two ring-shaped molecules to form a chain, called a catenane. His trick was to use a copper ion to pinch the two rings together as they formed. Then in 1991, Fraser Stoddart of Northwestern University created the first rotaxane molecule, which looks like a ring encircling a dumbbell. He also showed the ring could move along the axle. And in 1999, Bernard Feringa of the University of Gronigen developed the first molecular motor, using light and heat to make it spin. Hooking up four motors along a molecular chassis, he created the first nano-car and, when he applied light and heat, it drove itself along a surface. Molecular robots now promise to transform everything from medicine to cleaning up the environment.

PRIME MINISTER'S PRIZE FOR SCIENCE

# Thank you, cane toads

**Rick Shine won the $250,000 Prime Minister's Science Prize for penning a new chapter in the book of evolution. ELIZABETH FINKEL reports.**

Australian biologist Rick Shine has a lot to thank cane toads for. They may be an ecological disaster but they provided an extraordinary experiment in evolution.

What happens when you introduce 100 Latin American toads into a tropical corner of a vast dry country? They boldly go where no cane toad has gone before. Shine and his colleagues at the University of Sydney discovered that the "Captain Kirk" toads at the invasion front were unusual. They were the largest and fastest – and they evolved at a remarkably fast rate.

Since Shine's finding, researchers looking at migrating species from Monarch butterflies to Swedish voles have found remarkable individuals at the invasion front, speeding up the rate of evolution. In most cases, these species are on the move in response to climate change.

Unveiling this hidden facet of evolution is the jewel in the crown of Shine's illustrious career as a wildlife ecologist and netted him this year's Prime Minister's Prize for Science.

Shine didn't seek out the toads – they barged in on his 20-year project, which was using miniature radio transmitters to study the life history of tropical snakes at Fogg Dam, 70 kilometres east of Darwin. Snakes are his passion, and in pioneering studies like this one, he showed how they adapted to changeable rainfall and prey availability year to year.

But 70 years after toads were deployed to eradicate beetles from Northern Queensland's sugar cane fields, they arrived at Fogg Dam, nearly wiping out Shine's study. Snakes dined on the poisonous, large, slow moving toads and died. It was the same story for quolls and goannas at nearby Kakadu National Park. Instead of happily taking up residence in the dam, some toads marched on. These invaders were remarkable: not only were they extremely big, they scurried rather than leapt – much better for migrating across vast distances. Shine studied how such Captain Kirk toads arose and came up with the concept of "spatial sorting". The largest, fastest toads led. They bred with other fast toads, so in each generation, toads became faster. Shine recently compared the toads that just reached Western Australia with their ancestors from Queensland. Over 80 generations, they had developed slender bodies with long front legs. "Racehorse toads," Shine says.

SHINE DIDN'T SEEK OUT THE TOADS – THEY BARGED IN ON HIS 20-YEAR PROJECT.

At the same time, predator numbers recovered. The reason? The largest, most toxic toads moved on and left their babies behind. Little toads taste awful but are survivable. Black snakes adapted by becoming "pin-headed" – they could not physically swallow a toxic dose. Smarter predators, such as quolls and goannas, learnt how distasteful the tiny toads were and stopped eating them. "We never expected to detect evolution in a human lifetime; the speed of response is extraordinary," Shine says.

Taking a leaf out of nature's book, Shine has served up toad sausages to populations of endangered quolls in Kakadu National Park, successfully training their palates to reject the toads as food. "Blending evolutionary thinking with conservation is what I am most proud of," he says.

OPINIONS, IDEAS & PERSPECTIVES

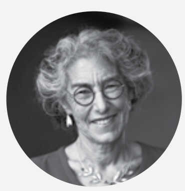
# VIEWPOINT


## "CAN YOU KILL ONE PERSON TO SAVE FIVE?"

LAURIE ZOLOTH — ETHICS

NORMAN SWAN
**BODY TALK**

KATIE MACK
**ASTRO KATIE**



LAURIE ZOLOTH
**PHILOSOPHER'S CORNER**

ALAN FINKEL
**INCURABLE ENGINEER**

NORMAN SWAN is a doctor and multi-award winning producer and broadcaster on health issues.

# BODY TALK

## Take the pressure down – mostly

**Lowering blood pressure may not be right for everyone.**

APART FROM SMOKING, the biggest risk factor for heart attacks and strokes is high blood pressure. It batters and weakens arteries and is also linked to heart and kidney failure. So it makes sense for doctors to prescribe treatments that lower blood pressure. But how low should doctors go?

Last year, a US study suggested doctors should aim to lower blood pressure further than traditional guidelines recommend. Now an August study warns that might not be a good idea for everyone.

Blood pressure is measured in millimetres of mercury (mmHg), a reference to the old-fashioned sphygmomanometers that doctors still sometimes use. They wrap a cuff around your arm, which is attached to a glass column filled with mercury, and pump up the cuff while feeling and listening to the pulse in the brachial artery just below it. The cuff pressure is increased enough to stop the pulse in the artery. Then with a whooshing sound, the air pressure is reduced until the doctor hears the thump thump of the pulse coming back. A reading of the mercury level indicates the systolic pressure, from the Greek word *sustolē*, meaning “to contract”. It’s a measure of the heart’s power stroke.

A normal reading is considered to be below 120 mmHg. More air is released, and the doctor listens for a switch to a softer thump or the sound disappears altogether. That’s the diastolic pressure, deriving from the Greek word for expansion, *diastole*. As the heart expands to refill, the elasticity of the blood vessels maintains a back pressure, which is crucial to keep blood coursing through the vessels and tissues in between heartbeats. Normal is considered below 80 mmHg.

Patients are considered candidates for treatment if their systolic blood pressure is above 140 mmHg. That’s based on studies that have correlated systolic blood pressure with risks of heart attacks and stroke. We used to use diastolic pressure, but it’s no longer considered as good a predictor of risk.

The question, then, is what should be the target? Until recently doctors thought it was good enough to get below 130mmHg. But in 2015, the American SPRINT (Systolic Blood Pressure Intervention Trial) study published in *The New England Journal of Medicine* found that in people with multiple risk factors such as heart disease and raised cholesterol, aiming below 120mmHg significantly reduced the chances of stroke, heart attack, heart failure and dying prematurely. It came at the price of having to take more medications plus some side effects, including dizziness.

So should 120mmHg be the new target? It depends who you are. Last August, researchers at John Hopkins University in Baltimore published a paper in the *Journal of the American College of Cardiology* that suggested this low target could cause hidden damage to the heart in people with low diastolic pressure by lowering it further.

In some people with arterial disease, their stiffened arteries have lost the elasticity to provide good diastolic pressure. The result can be that their systolic pressure is a high 140mmHg but their diastolic is a low 65mmHg.

The researchers suspected that if the diastolic pressure was lowered even further by the aggressive use of drugs, their coronary arteries, which supply oxygenated blood to heart muscle when the heart expands, might not do their job properly. A heart that is missing out on its oxygen starts suffering muscle damage – a first step on the way to heart failure.

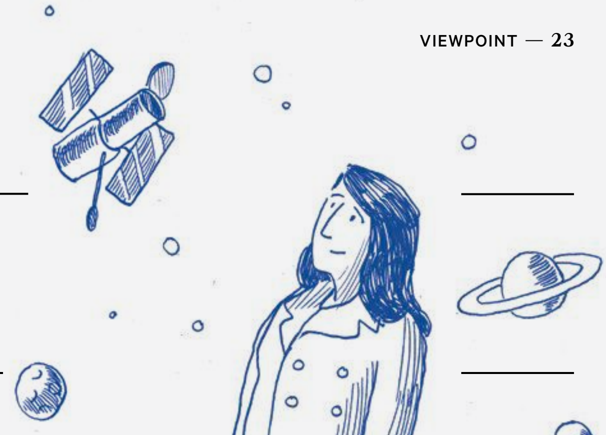
> THIS LOW TARGET COULD CAUSE HIDDEN DAMAGE TO THE HEART IN PEOPLE WITH LOW DIASTOLIC PRESSURE BY LOWERING IT FURTHER.

To test this idea, the researchers studied 11,500 people with an average age of 57 and compared their diastolic pressure with circulating levels of troponin – a protein that is released by a damaged heart. They found that people with a diastolic pressure less than 70 mmHg were more likely to have high troponin levels.

The take-away message for people being treated for high blood pressure may be that if they already have low diastolic blood pressure, then perhaps lowering blood pressure too aggressively could hurt their heart. In consultation with their doctor, they should take extra care until more studies are released that shed light on this perplexing and relatively ignored issue. ◉

KATIE MACK is a theoretical astrophysicist who focuses on finding new ways to learn about the early universe and fundamental physics.

# ASTRO KATIE



## ‘Goldilocks’ planets might not be so nice

**What does “habitable” really mean?**

THE RECENT DISCOVERY of a planet around Proxima Centauri, the closest star to our own sun, created immense excitement. Not only was the new world, called Proxima Centauri b (Proxima b for short), conveniently close to us – only about four light-years away – it was roughly the mass of Earth and just the right distance from its host star. A “habitable planet”!

But don’t fire up the generation ships just yet.

In the study of alien worlds, there is perhaps no designation more hopeful, or more misleading, than “habitable”. While it evokes a vision of a pleasant, temperate world, complete with breathable air and a human-friendly landscape, to an astronomer it means none of those things. While we would certainly classify our own planet as habitable, the term could be applied to any of a wide range of lethal nightmare planets, and Proxima b might be one of them.

We don’t really know what a planet needs to harbour life. Worlds inhospitable to humanity could be teeming with a kind of life we can’t even understand, possibly more alien than the “extremophile” life forms that populate subglacial lakes and hydrothermal vents. All we know is that for the kind of life that exists on Earth, liquid water is a necessity – at least intermittently.

With current technology, we don’t have the capability to conclusively detect liquid water on the surface of any worlds outside our own solar system, so we have to work with the information we have – the temperature of the star and the distance of the planet’s orbit. A planet too close to its star might be so hot that water would immediately boil off. Too far away, and it’s a solid ice world. The habitable zone is the sweet spot, the Goldilocks zone, in which the amount of starlight reaching the planet is just enough to allow water to exist on the surface in liquid form.

But there are some caveats, and they’re big. Distance isn’t everything when it comes to the temperature on a planet’s surface. In our own solar system, both Venus and Mars are often considered to be in the habitable zone. However, Venus has such a suffocatingly thick atmosphere that it’s undergone a runaway greenhouse effect; its surface is a sweltering 460 °C. The present-day atmosphere of Mars is so thin that liquid water can only appear briefly in salty rivulets on crater slopes on the warmest days of the year.

Studying the atmosphere of exoplanets is difficult. So far we’ve only been able to examine a tiny number of atmospheres, and none belong to rocky worlds in the habitable zone. But a problematic atmosphere isn’t the only thing that can render a world uninhabitable. In many cases, we don’t know for certain if a planet has a surface at all. In the case of Proxima b, we can tell that it’s at least 1.3 times as massive as Earth – and no more than three times – but if it’s over two, it’s probably more like Neptune, forgoing any solid surface for a thick gas and liquid envelope over a small, deep, rocky core.

Another wild card for Proxima b is its host star. Proxima Centauri is a red dwarf, much cooler and smaller than our Sun. This means Proxima Centauri’s habitable zone lies very close to it – so close that the gravitational interaction between it and its planet is extreme enough that Proxima b is probably tidally locked. This means that the same side of the planet faces the star at all times, in the same way our moon always shows us its same face.

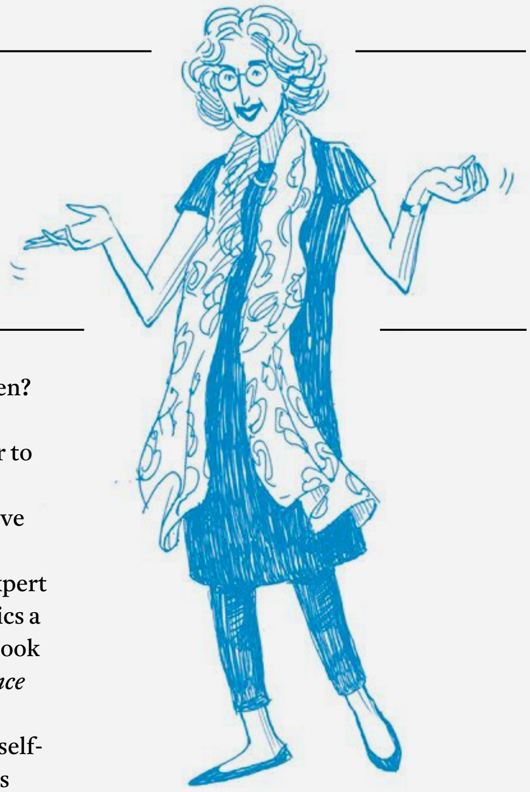
On such a world, rather than a temperate, circulating atmosphere, the day side might be boiling and the night side frozen. Even worse, Proxima Centauri is a flare star, meaning that it sends out giant flares of stellar material into space with alarming frequency. Even if Proxima b had a perfectly good atmosphere to begin with, it may have been stripped by its star’s unruly outbursts.

WHILE WE WOULD CLASSIFY OUR OWN PLANET AS HABITABLE, THE TERM COULD BE APPLIED TO A WIDE RANGE OF LETHAL NIGHTMARE PLANETS.

With future telescopes, some of them already under construction, we might soon be able to peer directly at Proxima b to analyse its atmosphere. In the meantime, we can only speculate and search for more habitable planets in the hope of learning more about our own origins. Perhaps someday we’ll find unmistakable signs of life on another world.

LAURIE ZOLOTH is a professor of medical ethics & humanities at Northwestern University, Chicago.

# PHILOSOPHER'S CORNER



## Putting machines in the driver's seat

**Self-driving cars: accidents may happen, but a machine behind the wheel is still the more ethical choice.**

LAST SEPTEMBER, Uber, the app-based ride service, rolled out a small fleet of self-driving cars in the US city of Pittsburgh. Reporters delivered breathless accounts, largely along the lines of: "Not me! I would never opt for a self-driving car!"

Two things unsettled the reporters.

One was the threat to their sense of autonomy. Self-rule is a core value in constitutional democracies, enshrined in a culture that deifies the lone cowboy or the lone driver setting off into the sunset. A car is often one's first major possession. In the California of my childhood, wide open freeways were an expression of individual choice and power.

The other thing that unsettled them was how the machines would act if faced with the "trolley problem". It's a favourite of every first-year ethics class. Imagine you are a trolley or tram driver on a set of fixed tracks and the brakes fail. Just ahead of you, a group of five people are crossing the tracks. You cannot stop, but you can pull a lever and switch the speeding trolley to a side track. Sadly, there is also a person crossing there. Can you kill the one to save the five? Most people say yes. Does it matter if the lone person is Einstein, and the five are members of a criminal gang? Does it matter if the one is your elderly parent and the five are innocent children? And do you want to make a rule for all trolley operators that it is always better to kill one to save five?

So how does the self-driving car solve this problem? I asked J. Storrs Hall, a Virginia-based artificial intelligence expert and author who has given machine ethics a great deal of thought. He published a book called *Beyond AI: Creating the Conscience of the Machine*.

Hall thinks the public worry about self-driving cars comes from mistaken ideas that they would employ some disturbing utilitarian machine ethics to come up with a solution. They wouldn't.

The trolley problem is just as unsolvable for a machine as it is for philosophers. In his view it's not actually a moral problem; it's a technical problem. You design the machine to cause as few accidents as possible. You test and compare the results with what human drivers actually do. And then you reiterate the process. It doesn't need to be perfect; it only needs to be better.

Ultimately, the question for an ethicist is: even with an imperfect algorithm, is the self-driving car a more ethical choice?

Hall and I agree: the answer is a resounding yes.

Nearly 1.3 million people die in road crashes each year – 3,287 deaths a day, on average. An additional 20 to 50 million are injured or disabled. More than half of all road traffic deaths occur among young adults aged 15-44. About 32% involve alcohol.

And that's just the tip of the iceberg when it comes to the thoughtless or downright criminal stupidity of drivers. Many other accidents are caused by driving under the influence of drugs, texting while driving or exhaustion.

The safety programming on a self-driving car would eliminate the risks imposed by such behaviours. Self-driving cars would also give autonomy to those who currently don't have it, like the aged and infirm.

There are other values to consider. Creating a car that is wildly technologically advanced instead of, for example, creating better public transportation systems is a choice for one sort of world over another.

SELF-DRIVING CARS DON'T NEED TO BE PERFECT. THEY ONLY NEED TO BE BETTER.

Like any technology, self-driving cars are not perfect. But stopping the needless tragedies on our roads means the choice to develop them is not even a close call. No doubt there will be mistakes and dreadful accidents. But by preventing risky behaviours in the first place, there would undoubtedly be less carnage than we have today.

In Hall's view, the real trolley problem is: how long do you leave the status quo versus speeding up the development of self-driving cars? I agree. In the not-so-distant future, the question for ethicists will be: why did we wait so long to fix this?

ALAN FINKEL is an electrical engineer, neuroscientist and the chief scientist of Australia.

# INCURABLE ENGINEER

## Breaking limits

**Human ingenuity keeps demolishing historical barriers.**

WHEN ACCEPTED LIMITS are broken, I am astonished. Often what I thought were hard limits turn out to be the limits of our collective imagination, not the imposition of physics.

Surprisingly, this demolition of apparently immovable limits happens often. Here are a few examples from my lifetime. See if you can think of a few of your own.

When I studied electrical engineering, it was generally accepted that copper telephone wires couldn't carry electrical signals that oscillated faster than about 5,000 cycles per second. That was good enough for voice signals, but made for very slow digital communication. As a rule of thumb, you could expect to transfer twice that rate as bits of data and, indeed, for a long time 9.6 kilobits per second was the standard.

But with the advent of new signal-processing techniques for modems, more sophisticated error-correction algorithms and circuitry improvements at telephone exchanges and distribution nodes, digital communications over the copper telephone network became progressively faster.

Today's high-speed data modems deliver download speeds of 10 megabits per second – 1,000 times faster than what I naively understood would be the upper limit of the ordinary copper telephone wires.

Moving on to water sports, when my sons were young I explained to them that the maximum speed of a sailboat is proportional to the square root of its waterline length. According to the hull-speed formula, the 27-metre boat used in the America's Cup race should have a maximum speed of 24 kilometres per hour.

Incredibly, the current generation of America's Cup sailboats average speeds of nearly 75 kilometres per hour, often running at twice the wind speed. How did they achieve this breakthrough? By changing the nature of sailing so that instead of ploughing through the water, the boats rise up on a hydrofoil and skim along the surface.

As a very amateur photographer and a manufacturer of scientific imaging systems, for decades I accepted that in order to get high-resolution, high-contrast images, you needed a large optical lens. The rule was "bigger is better".

Nowadays I see astonishing pictures from smartphone cameras that have tiny lenses only a few millimetres in diameter. I was stuck in the wrong paradigm. In the past, because conventional film – containing silver halide crystals – is inherently granular, it needed to be at least 35 millimetres wide to achieve high resolution.

When electronic sensors replaced film, they started off the same size in order to operate with standard-sized cameras and lenses. I never foresaw that, aided by clever image-processing software, high-resolution electronic sensors could shrink to fit into smartphones with a tiny matching lens. This breakthrough was achieved by accepting a compromise: smartphone cameras only operate well in bright conditions, with stationary subjects.

Finally to aeroplane wings. When you look at the massiveness of an A380, it is hard to believe that it can fly! Things have changed. Each square metre of the Wright Flyer biplane built in 1903 could lift seven kilograms. With today's technology, each square metre of an A380 can lift 663 kilograms. The reasons for this astonishing increase have to do with speed, materials strength and wing design.

I AM SURE THAT FUNDAMENTAL LAWS OF PHYSICS SUCH AS THE SPEED OF LIGHT WILL NEVER BE BROKEN.

I am sure that fundamental laws of physics such as the speed of light will never be broken.

But technological limits are no match for the march of human ingenuity. Developed millions of years ago to cope with the challenges of living on the African savannah, today this ingenuity is channelled into the efforts of scientists and engineers across the planet, sometimes converging in surprising breakthroughs.

HOLODECK:
COMPILED BY JAMES MITCHELL CROW

# BEFORE THE DINOSAURS

WELCOME TO THE DAWN OF THE PERMIAN, 290 million years ago. Reptiles with waterproof skin and eggs are colonising the land.

They are not dinosaurs, but synapsids: a group defined by the single hole in the skull behind each eye where jaw muscles attach. Mammals are synapsids too, so these creatures are more closely related to us than to dinosaurs.

Sail-backed synapsids, like the plant-eating *Edaphosaurus* on the right, are common. They can grow up to 3.5 metres long. The carnivorous *Dimetrodon*, at back left, is a little longer, reaching up to 4.6 metres. The sails on these species may have heated and cooled the body. Skulking in the left foreground is the massive-skulled *Ophiacodon*. These early synapsids are known as pelicosaurs.

CREDIT: JULIUS CSOTONYI

THE FIRST THERAPSIDS

By the mid-Permian, pelicosaurs are being displaced by therapsids. This group was becoming more mammal-like: their legs were positioned vertically under their body and they had three types of teeth – incisors, canines and molars. (A reptile's teeth may be different sizes but they are all the same shape). Some were also thought to have fur and be warm- blooded.

*Dinocephalians*, a sub-group distinguished by their interlocking incisors, dominated the mid-Permian. They weighed up to two tonnes. *Dinocephalians* included herbivores such as this herd of *Estemmenosuchus* or *Ulemosaurus*, represented by the fossil, and the carnivorous *Eotitanosuchus*, emerging from the water, which could reach a length of five metres. The whole group mysteriously disappeared around 270 million years ago.

CREDIT: (LEFT) JULIUS CSOTONYI (BELOW) GONDWANA STUDIOS

GORGONOPSIDS

*Gorgonopsids*, a later group of therapsids, were fearsome carnivores. The name refers to the Greek monster the Gorgon. Some of the largest examples include the three-metre-long *Inostrancevia* (see fossil), and the similarly sized *Dinogorgons*, shown here fighting over a carcass.

*Gorgonopsids* were characterised by their large, powerful jaws and sabre-teeth. But their mighty incisors could not save them from the biggest mass extinction event in Earth's history. Thought to have been triggered by a series of massive volcanic eruptions in what is now Siberia, 80-90% of plant and animal species disappeared in what is known as "The Great Dying". (See *Cosmos* 70, page 46.) It marked the end of the Permian and the start of the Triassic.

CREDIT: (LEFT) JULIUS CSOTONYI (ABOVE) GONDWANA STUDIOS

CYNODONT SURVIVORS

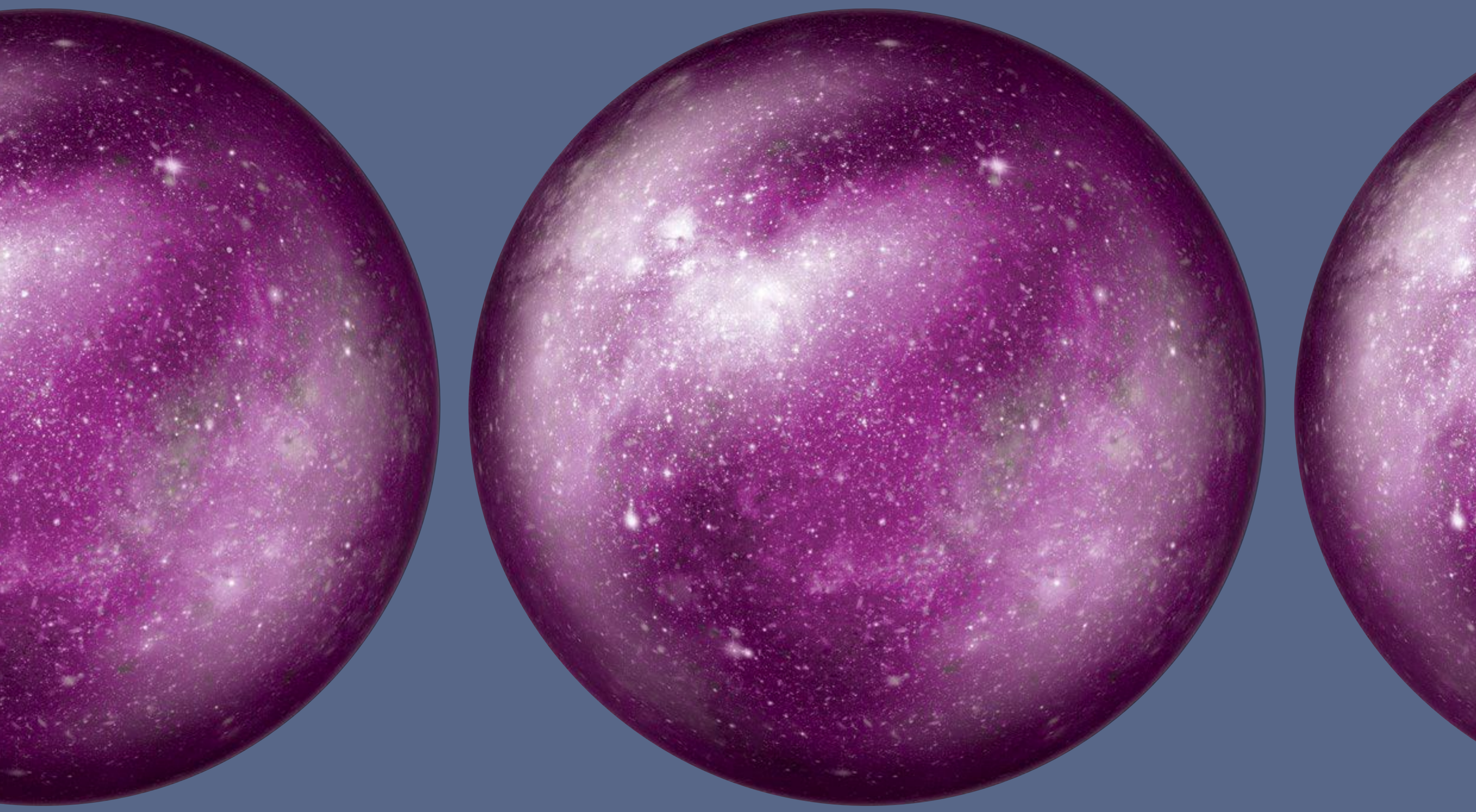
The therapsids were *almost* wiped out in the Great Dying, clearing the way for dinosaurs. They were diapsids – distinguishable by two holes in the skull behind each eye socket, like modern-day birds and lizards.

A handful of therapsids survived. Among them were the herds of herbivorous *Lystrosaurus*, shown at the water's edge and in fossilised form. And most importantly for us, the cynodonts: the ancestors of mammals. One is shown here edging out onto the finger of rock.

Little holes in the fossilised snouts of cynodonts suggest they had whiskers, which means they probably had fur and were warm-blooded.

The cynodonts lived in the dinosaurs' shadow for 200 million years, until a mass extinction triggered by a crashing comet favoured this ancient lineage once again.

CREDIT: (RIGHT) JULIUS CSOTONYI (ABOVE) GHEDOGHEDO / STAATLICHES MUSEUM FÜR NATURKUNDE STUTTGART



01

# MANY WORLDS

A surprising number of physicists entertain the possibility of other universes. So just how far-fetched an idea is it? DAN FALK investigates.

DAVID WALLACE was still in high school when he first encountered the notion of parallel universes. To a British teenager hooked on science fiction and physics, it sounded "weird but cool", he recalls. Twenty years later, the topic still absorbs him.

A PROFESSOR SPECIALISING in the philosophy of physics at the University of Southern California, he recently penned a book titled *The Emergent Multiverse*.

For some people, the idea there is more than one universe out there sounds absurd. Sure, it's fair game for the writers of *Star Trek*, and perhaps even for philosophers, but how can it be a serious *scientific* idea?

In fact, it was first put forward some 60 years by a very serious physicist, Hugh Everett III, who proposed the idea of "Many Worlds" as a way of making sense of quantum mechanics – the strange science of the subatomic world.

Everett's idea was *not* well received. But by the time Wallace was wrestling with quantum mechanics as a physics PhD student four decades later, the idea had been resurrected. "What was a revelation to me was realising that these parallel 'worlds' weren't something extra that you added to quantum mechanics; they were there in the mathematics of the theory all along. And it was realising *that* that got me thinking, 'Ok, this is probably right – or at least, this is the best route that we have at the moment to try to make sense of this'."

Quantum mechanics isn't the only theory that leads scientists to the idea of parallel universes. String theory – an attempt to stitch gravity into the equations that govern the quantum world by proposing the existence of 11-dimensional vibrating strings – also suggests our universe is just one of many in a vast cosmic landscape. Meanwhile inflation theory holds that our universe inflated as a bubble of space-time shortly after the Big Bang. If it happened once, then perhaps it happened many times and is still happening.

Of these various paths to parallel worlds, the one that emerged from quantum mechanics, now referred to as "Many Worlds", was the first out of the gate. It's rooted in mathematics, and it wouldn't be the first time that this esoteric language unveiled a hidden reality. The Big Bang, black holes and the concept of curved space, for instance, all first emerged from a scrawl of mathematical equations. Now evidence they exist is virtually bulletproof. We can hear the "echo" of the Big Bang – the cosmic microwave background radiation – with radio telescopes. Just last year, we detected the gravitational signatures of colliding black holes. And Uber drivers would be lost if Google Maps didn't take account of Einstein's curved space-time.

So can we find any evidence for the existence of Many Worlds? Probably not. But advocates say that's not a deal breaker. They consider Many Worlds to be just one more of the predictions of quantum mechanics – a theory whose other predictions have been exhaustively proved. Because of that, a surprising number of respectable physicists are willing to entertain the reality of multiple worlds.

CLUES TO THE WEIRDNESS of our universe began to emerge in the early 1900s when the founders of quantum physics, including Max Planck, Albert Einstein and Werner Heisenberg in Germany, along with Niels Bohr in Denmark, began to investigate the structure of the atom.

It was Planck who showed that energy came in discrete bundles or quanta. Einstein backed him up by showing that light radiates its energy as bundles that we now call photons. Yet for 100 years before that, light was understood to be a wave. Now scientists were forced to think of light as *both* a particle *and* a wave.

Then in the 1920s, a young Frenchman named Louis de Broglie argued this type of behaviour wasn't restricted to light: any kind of particle should display this duality. He described the idea of "matter waves" in his doctoral thesis in 1923. The counterintuitive notion almost cost him his degree, until Einstein gave it a nod of approval.

Bizarre as the idea was, Austrian physicist Erwin Schrödinger nevertheless found he could describe matter waves with a mathematical equation called the "wave function".

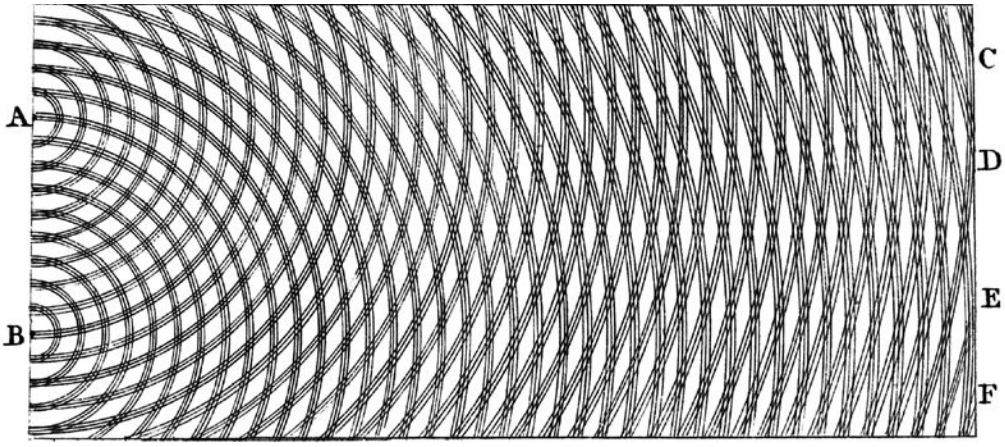
Schrödinger's equation did not describe a world that we experience. Tracking a subatomic particle was nothing like describing the position and velocity of a fired cannonball. Rather, his wave function described particles as some sort of statistical entities. All one could do was describe the likelihood of where and when to find them. Schrödinger attempted a grasp on reality by imagining matter waves as being something like "smeared-out" particles.

That's exactly what American physicists Clinton Davisson and Lester Germer, working at Bell labs, found when they accidentally performed a version of the double slit experiment.

Their original intention had been to figure out the structure of a nickel crystal by firing electrons at it and measuring the angles at which they scattered off its surface. Instead of revealing something about the nature of the crystal, they revealed something startling about the nature of electrons. The crystal had provided the equivalent of tiny slits. And travelling through them, the electron beam produced an interference pattern – just as light waves do.

The experiment was undeniable proof of the bizarre nature of reality that has continued to shake

02




Like ripples on a pond, light waves interfere each with each other. Thomas Young first observed this in 1803 using the double slit experiment, and explained the result with this sketch.

'ANYONE WHO IS NOT SHOCKED BY QUANTUM THEORY HAS NOT UNDERSTOOD A SINGLE WORD.'

Of all the tests of quantum mechanics conducted over the years, the one that sheds the most light on this weird science is the decidedly low-tech double slit experiment. Back in the 19th century, British polymath Thomas Young first used it to show the wave nature of light. Aim a beam of light at a sheet with two thin, rectangular slits cut into it. The light passes through the slits and projects onto a screen. But what you see on the screen is not two bars of light – rather, you get an "interference pattern" – an array of light and dark patches. It's the signature pattern produced by interfering waves, similar to that made by ripples on a pond. The peaks or bright patches are where the crests of light waves meet other crests; the dark patches are where the crests meet troughs, cancelling each other out.

That's fine for light – already known to behave like a wave – but what about bits of matter? The work of de Broglie hinted that tiny particles such as electrons would behave in an identical fashion.

physics ever since. "Anyone who is not shocked by quantum theory has not understood a single word," Bohr said.

How can an electron, a particle of matter, be a wave? Stanford physicist Leonard Susskind expressed his discomfort this way on YouTube: "A rock is an example of a particle; an ocean wave is an example of a wave. Now someone's telling you a rock is like an ocean wave. What?!"

Things get even more bizarre. More sophisticated versions of the double slit experiment were carried out using an electron gun, with the rate of firing slowed so that only one electron was released at a time, passing through one of the two slits. Yet over time, an interference pattern emerged on the phosphor-coated screen behind it. It was as if the single electron was passing through both slits at the same time and interfering with itself, so to speak. This ability to be in two places at the same time is termed *superposition*.


WERNER HEISENBERG
MAX PLANCK
NEILS BOHR
ALBERT EINSTEIN
THE FOUNDING FATHERS OF QUANTUM PHYSICS
THOMAS YOUNG
DISCOVERS THE DOUBLE SLIT INTERFERENCE PATTERN FOR LIGHT WAVES
YES! IT WORKS FOR PARTICLES TOO!
IF LIGHT WAVES CAN BEHAVE LIKE PARTICLES...
CAN PARTICLES BEHAVE LIKE WAVES?
LOUIS DE BROGLIE
(ALSO LOUIS DE BROGLIE)
CLINTON DAVISSON
LESTER GERMER

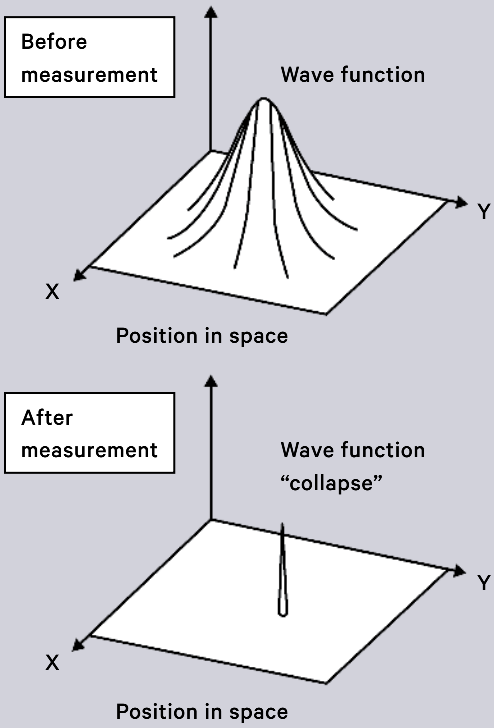

MY WAVE FUNCTION DESCRIBES THE BEHAVIOUR OF PARTICLE WAVES!
ERWIN SCHRÖDINGER AND HIS EQUATION
SMEARED PARTICLES (AN ARTIST'S INTERPRETATION)
THE OTHER CAMP
THE COPENHAGEN CAMP
SOMETHING IS MISSING!
THE MATHS WORKS OK?
SHUT UP AND CALCULATE!
SCHRODINGER
EINSTEIN
HEISENBERG
BOHR
AGE OLD PHILOSOPHICAL DEBATE
HI HUGH, I'M ALSO HUGH...
COSMOS
THE MANY HUGH EVERETTS OF HUGH EVERETT'S MANY WORLDS
J. PHILLIPS 2016

Somehow, this was just one more of the amazing properties of the wave function. Not only was an electron to be thought of as a haze of probabilities (that nobody really understood), it could exist in two places at the same time.

But what happened to the electron's haze of probabilities when it hit the phosphor screen? Suddenly all those probabilities collapsed into one point. It's as if an ocean wave, at the moment of wetting the shore, suddenly shrank to wet only one grain of sand. Something about the very act of detection led the wave function to collapse and behave like a particle.

THE COPENHAGEN INTERPRETATION

The act of measurement causes all the possible positions of the wave function to collapse into a single point. What happens to the other positions? According to Hugh Everett, they split off into other worlds.




Israeli scientists in 1998 vividly demonstrated this "observer effect". When a device akin to a Geiger counter was positioned to detect electrons as they approach the slits, the screen on the other side no longer recorded an interference pattern. The act of observing them reduced them to behaving as mere particles.

How did physicists explain this assault to our understanding of reality?

One response was not to try. As Bohr put it, "there is no quantum world. There is only an abstract quantum physical description", while Heisenberg offered, "what we observe is not nature itself, but nature exposed to our method of questioning".

In a sense they rejected the reality of quantum world while accepting that the mathematics of the wave function accurately predicted its behaviour. And in fact, the wave function has proved to be uncannily accurate, enabling us to predict the nature of chemical reactions, the development of lasers, electronics, computing and quantum encryption methods – technologies that provide 25% of the US gross national product. For Bohr and Heisenberg, the fact that the mathematics worked was the end of the story. They represented the so-called "Copenhagen interpretation", also known, somewhat snarkily, as the "shut up and calculate" school of thought.

But other physicists, including Einstein and Schrödinger, felt something was missing. They remained troubled about what quantum mechanics said about the nature of reality. The two camps were reprising an age-old philosophical debate about the meaning of mathematics. Is mathematics merely a useful abstraction, as the Copenhagen-ists argued? Or does it point to a hidden reality?

FOR DECADES, the Copenhagen interpretation was the only game in town. Then in the 1950s, Hugh Everett, working on his PhD at Princeton University, issued a bold challenge. He had been wondering about the critical concept at the heart of quantum mechanics, the collapse of the wave function when a measurement is made. What exactly causes it to collapse, eliminating all possibilities but one?

Apparently after a night of drinking with friends, he came up with a radical answer: *the wave function doesn't collapse*. Instead, all possibilities occur, but in different universes. When we make a measurement, the universe branches to accommodate those different outcomes. And since just about any physical interaction involves quantum processes – the world is, after all, made up of atoms. This splitting, then, is happening all the time, creating an infinity of universes, each being a slightly altered doppelgänger of our own.

Everett's thesis advisor John Wheeler, excited by his student's theory, travelled to Bohr's institute for theoretical physics in Copenhagen with a copy of the Many Worlds thesis. Neither Bohr nor his colleagues were impressed. Alexander Stern, an American scientist working at Bohr's institute, described it as "theology".

Wheeler wrote to Everett, saying: "Your beautiful wave function formalism of course remains unshaken: but all of us feel that the real issue is the words that are to be attached to the quantities of the formalism." In other words, Wheeler was worried that people might think Everett was serious about those other worlds actually existing. (In fact, Everett *was* serious about them.)

Wheeler talked Everett into removing references to split worlds; his thesis was eventually whittled down to a quarter its original length. Everett acquiesced because he needed his PhD to land a job. He ended up leaving theoretical physics to take a position at the Pentagon as a weapons strategist. During his years there, his mathematical models looked at scenarios such as the catastrophic death rate from radioactive fallout in a nuclear war, helping to develop the concept of mutually assured destruction. Perhaps we have Everett to thank for having any world at all.

For Wallace, the Cold War atmosphere helps explain the intolerance for Everett's ideas. Many labs emphasised applied science over abstract theorising with an emphasis on building weapons. "You had a longish period where theoretical and conceptual questions were subordinated to a very practical attitude to physics," says Wallace.

But beginning in the 1980s, a new openness for bold, unconventional thinking took hold and Many Worlds made a comeback. This was partly because the older generation of physicists – the ones who had worked alongside Bohr, Heisenberg and the rest of the gang – had retired or died, but also because the need to understand the quantum world grew ever more compelling. The boundary between the quantum and classical worlds had become hopelessly blurred. In 1991, a team at the University of Vienna carried out a double-slit experiment to demonstrate the wave-particle duality of some very big particles – "buckyballs" composed of 60 carbon atoms. In 2013, the university did it again with a molecule composed of 800 atoms.

Quantum weirdness has also entered our world with some down-to-earth applications – most notably, the drive to develop a quantum computer. Their bits are composed of atoms that have a spin state that can be either up or down. But it turns out they can also be in a state of superposition – simultaneously up and down. Quantum computers take advantage of these superpositions to perform calculations that some claim will be billions of times faster than conventional computers in some cases.

The more that quantum weirdness leaps out of the textbooks and into the laboratory, the less adequate the Copenhagen interpretation seems – and the more willing physicists are to consider the alternatives. "All of these things, I think, brought the question of what the [Many Worlds] theory actually means back onto the table," Wallace says.

The idea of Many Worlds suffers from an obvious flaw. We may never be able to find a way to either prove or disprove their existence. And as 20th-century philosopher Karl Popper argued, a theory has to be falsifiable to even qualify as science.

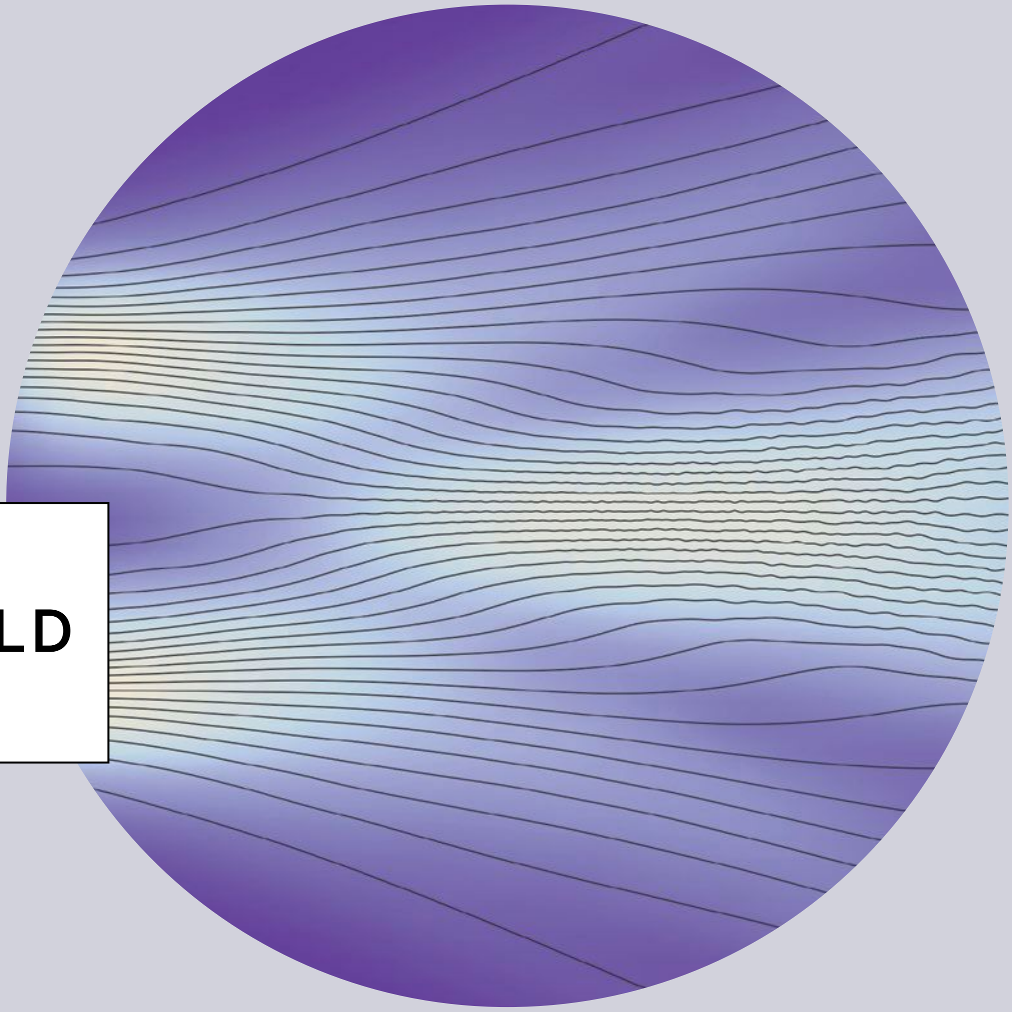
But Wallace says this does not disqualify Many Worlds. He and other proponents are quick to argue that Many Worlds is a *prediction* of quantum mechanics – itself probably the most exhaustively tested theory in history. "There's no general principle in science or in physics that says, 'theories that postulate lots of stuff are bad'," says Wallace. "There's just a principle that says, 'theories that postulate stuff that don't pull their weight, that don't have explanatory power, are bad'."

SOMETHING ABOUT THE VERY ACT OF DETECTION LED THE WAVE FUNCTION TO COLLAPSE AND BEHAVE LIKE A PARTICLE.

AND MANY RESPECTABLE physicists say that as far as explanatory power, Many Worlds is just as good as wave functions that collapse as soon as they feel they are being watched. "All physicists agree the maths of quantum mechanics tells us we have to fundamentally change our picture of reality in some way," says Michael Hall, a mathematical physicist at Griffith University in Queensland. "The Everettian Many Worlds interpretation is no better or worse than others in this regard."

Howard Wiseman, a theoretical physicist and Hall's colleague at Griffith University, puts it more strongly. "Many Worlds is certainly an obvious interpretation of the theory; it is even arguable that it is the simplest. Until, or unless, we get new experimental evidence on the matter, I think we should take all well-formulated interpretations seriously and see where they lead, scientifically and philosophically." The two Australian physicists recently published their own variation on a Many Worlds theory – see box.

Sean Carroll, a theoretical physicist at California Institute of Technology, agrees. "Our job as physicists is to construct a theory that does the best job of providing an accurate account of the observations – and then to take that theory seriously." Carroll also finds Many Worlds offers



# MODERN MANY-WORLD THEORIES

The MIW theory predicts the results of the double slit experiment. A 'repelling' force between worlds causes particles to follow curved paths.

CREDIT: MICHAEL HALL

IN FEBRUARY 2012, Howard Wiseman at Griffith University in Queensland was hosting a colleague, Dirk-Andre Deckert from the University of California, Davis. As quantum physicists are apt to do, the conversation soon turned to the "wave function" that describes the behaviour of particles in the subatomic world. Ninety-one years after its mathematical description, just *what* is actually being described remains open to interpretation.

"We thought perhaps we could come up with something that would offer better simulation methods for chemical reactions," Wiseman says. "But we ended up being radical; we threw away the wave function."

The duo focused on two interpretations. One was Everett's Many Worlds proposal, which states that the wave function never collapses. Instead, at the moment of measurement, the different outcomes are realised in different worlds that never interact with each other. The other interpretation, known as de Broglie-Bohm, was worked out by Louis de Broglie in 1927, and again, independently, by David Bohm in 1952. In this view, every particle is viewed as a real physical entity, surfing atop a probability wave.

Both interpretations have problems, Wiseman says. Everett's theory was vague on when world splitting took place and whether the worlds were equivalent. De Broglie-Bohm, meanwhile, had all the structures of Everett's theory but labelled only one world as being real. "I was excited by the idea of getting rid of these difficulties by melding the two interpretations," Wiseman explains.

Wiseman turned to his colleague Michael Hall, a mathematical physicist at Griffith University, to help model an alternate multiple world scenario.

They were not the first to do so. Many Worlds scenarios have been making a comeback in the last few years. What's different about the latest models is that unlike Everett's worlds, these interact.

For instance, William Poirier, a physical chemist at Texas Tech University, published a version in 2010. In his model, the quantum effects arise from stresses and strains within a fluid-like continuum of worlds. The version crafted by Hall, Deckert and Wiseman was published in 2014 in *Physical Review X*. Dubbed "Many Interacting Worlds" (MIW), it holds that there is no wave function; rather its job is done by other worlds just as real as our own. They are numerous, but finite. Every particle in every world has a definite position and speed. The more similar these worlds are to our own, the more strongly their particles interact with ours.

So does their model make testable predictions? Wiseman says they are still at the stage of validating their model to see if it does as good a job as the wave function at describing quantum effects. So far it has succeeded in modelling the results of the double-slit experiment (diagram above).

Wiseman says they can also use it to calculate the ground states of electrons, but not yet their excited states. "As I see it, the theory doesn't have drawbacks. That's *not* to say it's easy." Significantly, if the number of universes is finite, the MIW's predictions turn out to be ever-so-slightly different from those of standard quantum mechanics. "This does bring some hope that perhaps our interpretation is directly testable," says Hall.

The MIW model has received plaudits from colleagues. According to Charles Sebens, a philosopher of physics at the University of California, San Diego, who also came up with a theory of interacting worlds, MIW "gets you back to this picture that we haven't had in physics for a long time – of particles interacting with each other through forces".

And then there's the question of whether the Queensland physicists think their model has anything to with reality. Hall is sceptical. "You need an awful lot of reality in MIW." But he adds, "I'm sceptical about all interpretations." Wiseman, on the other hand, says he is "open-minded" and finds the MIW approach "quite compelling".

the most succinct way of making sense of quantum theory. "There's nothing that you have to put into quantum mechanics to make Many Worlds happen. To *stop* Many Worlds from happening, you have to change quantum mechanics somehow."

The fact that we can't test for other universes doesn't bother Many Worlds enthusiasts. After all, this isn't the first time that a theory of physics has predicted something that's beyond our ability to investigate. Einstein's theory of general relativity, for example, makes predictions about the interior of black holes – a realm that no human will ever enter (or at least, return from). We accept these ideas even if we can't test them, because general relativity has been extraordinarily successful in many different realms.

The champions of Many Worlds theories ask that we treat the predictions of quantum theory with equal seriousness.

OF COURSE THERE ARE legions of detractors. Massimo Pigliucci, a philosopher of science at the City University of New York, is often to be found immersed in discussions – perhaps arguments is a better word – with Carroll, over the merits of the Many Worlds view (both of them are prolific bloggers, and neither is particularly shy). "Sean keeps telling me, 'the mathematics are perfectly clear.' But it's not a question of the mathematics being clear – it's a question of the metaphysics being clouded," Pigliucci says. On several occasions he's asked Carroll where, exactly, the "parallel Massimos" are located – and he's never been satisfied with the answer. "It seems like the whole thing is predicated on a confusion between mathematical and physical reality," says Pigliucci.

But others are prepared to follow the equations wherever they lead. And if that means there are parallel versions of each of us "out there", so be it. The cosmos is a weird place. But then, as Wallace points out, nature has no obligation to conform to our expectations.

'TO STOP MANY WORLDS FROM HAPPENING, YOU HAVE TO CHANGE QUANTUM MECHANICS SOMEHOW.'

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DAN FALK (@danfalk) is a science journalist based in Toronto. His books include *The Science of Shakespeare* and *In Search of Time*.

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ILLUSTRATION
Jeffrey Phillips

# BUILT TO KILL

From the blue-ringed octopus to cone snails, nature's poisonous creatures have evolved clever ways to off their prey. CHRISTIE WILCOX reports.

→ AUSTRALIA'S BLUE-RINGED OCTOPUS is named for the iridescent blue rings that signal its deadly nature to potential predators.

01

PAINLESS. That’s the word used by victims to describe the bite of a small octopus found in Australian tide pools.

ONLY ABOUT THE SIZE of a golf ball with patterned, brownish to yellowish skin, the species in the genus *Hapalochlaena* are all shy, preferring to avoid contact with humans, or pretty much anything else larger than they are. They spend their days hiding, using their colour-changing skin cells (chromatophores) to blend in with their environment, or tucking their gelatinous bodies into crevices in the rocks and reef. Though the species are modest in size and temperament, they are armed with some of the most potent venoms in the world. All of them are referred to by the same common name, which comes from the distinctive skin pattern they display when afraid: deep, peacock-blue circles. Blue rings of death, as they have been called. A final warning from the blue-ringed octopus. Painless. But deadly.

Anthony and his twin brother didn’t know it was dangerous – they were, after all, only four years old in 2006 when they discovered a small octopus in the rocky tide pools at Suttons Beach in Queensland, Australia. The boys’ mother, Jane, said she saw Anthony playing with the little animal shortly before he complained that it had bitten him. The young boy began vomiting almost immediately. His vision blurred and he quickly lost the strength to stand. “He said to me, ‘I can’t walk,’ and his legs were all floppy,” she reported. Luckily, he was quickly in the hands of emergency responders who knew exactly what was causing the sudden and severe symptoms (though bites aren’t incredibly common, the blue-ringed octopus’s reputation is now well-known by first responders in the areas where the deadly cephalopods occur). They rushed him to the hospital as he laboured to breathe. He soon lost control of his muscles altogether, and had to be transferred to pediatric intensive care. Less than 30 minutes after the bite, the boy was dependent upon a ventilator for survival. It would be another 15 hours before Anthony’s body managed to clear the toxin enough that he could begin to move his muscles on his own, and more than a day before he was strong enough to be discharged.

If he had been any further from medical care, or could not describe his assailant, Anthony likely would not have survived. A similar creature killed a full-grown man just over half a century earlier, before first responders knew that blue-ringed octopuses were armed with such potent venoms. Kirke Dyson-Holland – or “Dutchy”, as he was known to friends – was 21 in 1954 when he went spearfishing with his friend John about five kilometres from Darwin, Australia. They were strolling along the tide pools near the beach when they spotted a little reef octopus. Believing it to be good bait for future fishing efforts, John picked up the animal and let it crawl over his arms and shoulders. He and Dutchy had played with octopuses before and never had cause for concern. John soon handed the small creature to Dutchy, who also let it wander over him as he walked, until it made its way to the back of his neck. Dutchy didn’t feel the brief bite, but a few minutes later, his mouth went dry. As he walked away from the water’s edge, he started vomiting. Struggling to breathe, he fell to the sand. John got him off the beach and to the hospital. One of the last things Dutchy said to his friend before losing the ability to speak was: “It was the little octopus, it was the little octopus.” He died two hours later.

At the time, Dutchy’s death was presumed to be from an allergy to the octopus’s saliva – an unfortunate medical complication. Even a decade later, when Bruce Halstead compiled and wrote one of the most-cited tomes on toxic animals ever published, *Poisonous and Venomous Marine Animals of the World*, little was known about the venom of octopuses and their relatives, and life-threatening bites and deaths were considered aberrations. But in 1970, the Australian scientists Shirley Freeman and R. J. Turner isolated the most lethal component from the venom of one such little octopus (*Hapalochlaena maculosa*), calling it *maculotoxin* in the absence of knowledge of its chemical composition. When injected into rats and rabbits, the compound caused steep drops in blood pressure and heart rate, and could completely paralyse the animals' respiratory systems. Eight years later, scientists confirmed that maculotoxin was, in fact, the same compound as is found in the flesh of pufferfish: the infamous tetrodotoxin.

Tetrodotoxin is among the deadliest compounds known to man. It's more potent than arsenic, cyanide or even anthrax. It's 120,000 times as deadly as cocaine and 40,000 times as deadly as methamphetamine. Like most of the world's most lethal compounds, it is a neurotoxin – it targets our body's nervous system. Unlike the haemotoxins in rattlesnakes and spiders, neurotoxins are fast-acting killers. They numb and incapacitate by inhibiting communication between cells.

The cells in our bodies have several ways of communicating, but the fastest is through electrical signals. Electricity isn't just in wires and batteries; it is, by definition, the energy that results from the existence of charged particles. Any time you have a barrier where there is more charge on one side than the other, there is the potential for movement should that barrier break down. That's literally what voltage is a measurement of – *potential* energy caused by differences in charge.

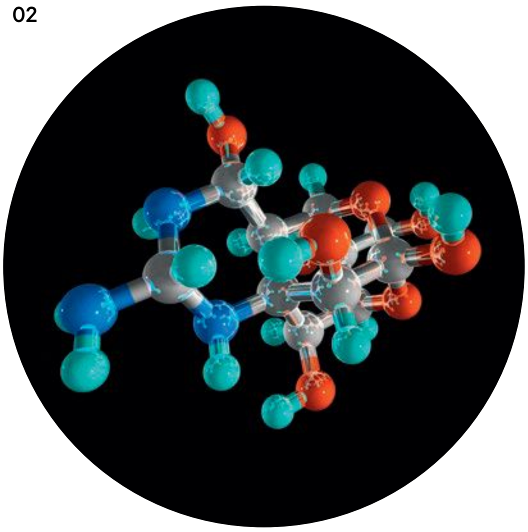
Your cells are essentially micro-batteries, with the cell membrane acting as the barrier between two differently charged solutions. Your average cell has a resting potential of -70 millivolts (mV), which simply means that there are slightly more negative charges inside a cell than outside. Cell membranes maintain this potential constantly, using energy to actively pump out sodium ions that sneak in, and pump in potassium ions that leak out. More importantly, the nervous system uses these membrane potentials to send lightning-fast signals to and from different parts of the body along long, skinny cells called neurons.

To type this paragraph, my brain has to send signals to the muscles in my fingers to tell them when and how to move. When my skin cells touch the keyboard, the pressure causes mechanoreceptors just beneath my skin's outermost layer, the epidermis, to activate, opening force-sensitive ion channels, thus allowing a sudden influx of sodium into the cell. For a brief moment, there is more positive charge inside than out, and the potential of the small section of membrane around the ion channel that was opened when I touched the key becomes +30 mV. Then the force-gated channel shuts.

Nearby on the membrane are similar ion channels that respond to changes in voltage rather than force, so when sodium ions flood into the cell, they swing open. Some of these are potassium channels that serve to return the membrane to the way it was – positive outside, negative inside – by letting potassium rush out of the cell. When the membrane is back to the way it should be, these shut, and active pumps on the membrane slowly return the sodium and potassium ions to the side of the membrane where they belong. All along the membrane there are these voltage-gated channels, so once one is triggered, the movement of ions sets off the next closest. That voltage-gated sodium channel swings open, and the whole process is repeated just a tiny bit further down. This domino-like cascade is how the electrical signal moves from one end of a long neuron cell to the other, eventually telling my brain that my finger felt something. The ions travel at very fast speeds across very small distances, and the opening and closing of ion channels happens very, very quickly. These channels are what neurotoxins attack.

**TETRODOTOXIN IS AMONG THE DEADLIEST COMPOUNDS KNOWN TO MAN. IT'S MORE POTENT THAN ARSENIC, CYANIDE OR EVEN ANTHRAX.**

02



A molecule of tetrodotoxin, a powerful neurotoxin found in the venom of the blue-ringed octopus.

Tetrodotoxin, for example, is a sodium channel blocker. When a blue-ringed octopus bites, tetrodotoxin in the venom shuts down the victim's neuronal signalling, leading to numbness radiating from where it entered the body. Nausea, vomiting and diarrhoea follow. Weakness and paralysis aren't far behind; the brain simply cannot tell the muscles to move. Even breathing requires electrical signalling – tetrodotoxin slows and eventually stops the diaphragm altogether. At high enough doses,

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A pufferfish is one of many animals that arms itself with deadly tetrodotoxin.

the victim's heart is unable to beat.

But tetrodotoxin isn't a universal toxin. That's because not all sodium channels are the same: even within our own bodies there are many variations on the same general theme. Tetrodotoxin can be deadly because it strongly binds to a range of sodium channels that are found crucially throughout our bodies and those of other vertebrates, but there are other variants of sodium channels that it isn't effective against. The blue-ringed octopus are wholly unaffected by their own venom component, and they're not the only species. Tetrodotoxin is wielded either as a weapon or a defence by salamanders, frogs, crabs, sea stars and even snakes in addition to the pufferfish, and all are either resistant or immune to its effects.

Just how many channel types are there? A lot more than you'd think. Potassium channels, for example, are made from a combination of four protein parts. We have 70 or so different genes for these parts, so if you made a channel using four exact copies from one gene, we'd have 70 different potassium channels. But it turns out that combinations work, too – you can have three of one and one other, or all four pieces completely different. Theoretically, there are upwards of 24 *million* different combinations, though scientists have yet to determine if all of them exist or what they do. What we do know is that our bodies employ a plethora of them, each with a different purpose. Some are found only in brain neurons, while others dominate the motor neurons that talk to muscles. Channels for other ions are similarly diverse.

Venoms from diverse species contain neurotoxins that affect every step of our neuronal signalling. Some, like tetrodotoxin, shut down critical channels, while others pry them open. Some stop signals at the very beginnings or ends of these pathways. Some indiscriminately act on a broad range of a given channel type, while others are incredibly specific. Tetrodotoxin is an example of the former – a brute of a neurotoxin, which is lethal in most animal species because it acts on many different types of sodium channels. On the other end of the spectrum are the toxins employed by another group of marine mollusks – compounds known for their elegance, for each has a very specific molecular target. Like artisanal mixologists, these snails craft intricate, unique venom cocktails that precisely incapacitate their prey. And when it comes to paralysis, no group compares to the impressive cone snails. These molluscs pack potent venoms, ones that still remain a rich source of new toxin sequences for scientists such as Baldomero Olivera, even though he's studied them for almost 50 years.

"I had not really intended initially to work on this for very long," he explains to me as we walk through the extensive malacology (mollusc science) collection at the Bishop Museum in Honolulu. The cool, somewhat dark hallways are lined floor-to-ceiling with grey metal cabinets full of shells. Baldomero – or Toto, as he is known by friends and colleagues – is one of the world's experts on cone snails. He first began studying their deadly venoms in the late 1960s. As a neuroscientist, he was intrigued by species with toxins that attack neurons, and cone snails were an obvious choice. "Because I had collected shells as a kid, I knew that these snails were capable of killing people."

Cone snail venoms cause near-instantaneous paralysis in their prey. They don't normally strike at humans ("You have to do something fairly stupid to [get] stung," Toto says), but more than a dozen deaths have been caused by their venoms, most of which are attributed to one species in particular: the geographer's cone, *Conus geographus* – the first cone snail Toto ever studied.

**CONE SNAILS CRAFT INTRICATE, UNIQUE VENOM COCKTAILS THAT INCAPACITATE THEIR PREY.**

He initially set out to discover what made the geographer's cone so deadly, and began by injecting the venom into the abdomen of mice. The furry test subjects were then placed upside down, clinging to a wire mesh. As the venom spread through their little bodies, it caused sweeping paralysis, and eventually the animals would fall. That was the experimental test Toto used to isolate the paralytic compounds: falling mice. He carefully separated the venom components through various size or chemical filters, slowly pinpointing exactly what parts of the venom were responsible for the paralytic activity. He was able to narrow it down to peptides – small proteins less than 20 amino acids long, which have come to be known as conotoxins – and after several years of research, he discovered two potent conotoxins: one that acts much like tetrodotoxin, shutting down sodium channels, and one that is similar to venom toxins found in cobras.

He had solved his quest, and had enough funding to afford better equipment. It was time to move on. He put his cone snail research on a backburner, tended by students. But then, a 19-year-old student named Craig Clark changed everything. Craig had an out-of-the-box idea: instead of just injecting the venom components into the mouse's body, he thought they should inject them into the mouse's central nervous system. Craig went on to do what he proposed, and made a startling discovery: many of the venom components overlooked in the falling test had effects in mice when injected into their brains, and the effects were weird. Some peptides caused mice to jump and twist. Others made them run in circles. One even put them to sleep, but only if they were less than three weeks old – it made adult mice run from one corner of the enclosure to the other.

With new fancy equipment, including an HPLC that allowed for fine-scale separation of each peptide, Toto and Craig discovered an unexpected diversity of conotoxins. "Suddenly we realised that the venom was not a few paralytic toxins but was this incredibly complex diverse pharmacological mix ... That experiment changed everything."

**MANY VENOMOUS ANIMALS HAVE TOXIN GENES WITH HIGH EVOLUTIONARY RATES.**

After Craig's incredible insight, Toto went on to host a "troop" of undergrads. Each could choose any cone snail they wanted; then they would use Craig's test and purify the conotoxin that caused the activity of their choice. One undergrad in the early 1980s decided to purify a compound he called the "shaker peptide", because the mice that received it would have characteristic tremors. His name was J. Michael McIntosh, studying the magic cone, *Conus magus*, and the peptide he discovered was called omega-conotoxin MVIIA. Nowadays, though, it's known by a different name: Prialt, the first FDA-approved drug from cone snail venom.

meal from wriggling away. That's just not fast enough for a snail to reliably catch a fish. We also know they have faster-acting toxins: videos of fish-hunting cone snails show that when they strike, their meal is frozen in the blink of an eye.

A completely different set of toxins causes that initial paralysis: what Toto calls the *lightning-strike cabal*. Instead of turning off channels, this cabal – dominated by the delta and kappa classes of conotoxins – flings them wide open and keeps them that way. The result is a flood of action potentials radiating from the sting site, as if the fish is getting electrocuted. Muscles throughout the body receive the signal to clench over and over, and the fish becomes instantly rigid throughout.

The lightning-strike–motor cabal combo is just one of the ways fish-hunting snails catch their meals. Other snails have different hunting strategies, such as putting whole schools of fish into an insulin coma, and relying on other cabals to precisely manipulate their prey. And recently, scientists discovered that cone snails don't just make toxins to kill – they make a different set of toxins to defend themselves with, and are able to wield these distinct predatory and defensive venoms as circumstances require.

04

A geograhper's cone snail (*Conus geographus*), the most venomous of all cone snail species, kills fish by delivering a potent mixture of toxins through its long proboscis. Its venom is also deadly to humans.

But this is still only scratching the surface of cone snail venom diversity. The toxins that shut down motor neurons are what Toto refers to as the *motor cabal* ("because cabals are secret societies out to overthrow existing authority," he explains). Every toxin in the motor cabal is able to paralyse a fish, but because they all work by shutting down the neurons directly, they are slow-acting. It takes about 20 seconds for motor cabal conotoxins to move via the circulatory system around the fish's body and reach enough neurons to stop the snail's

Suddenly, it makes sense why each cone snail species has so many conotoxins. But *how* did they come to have such diversity? No two cone snail species possess the same peptides; each has its own unique set, and there are more than 500 species in the genus *Conus,* more species than any other genus in the oceans. And the cone snails are just the beginning: Toto estimates that if you look at the extended family tree of the cone snail, there are more than 10,000 venomous marine snail species on the planet, each with anywhere from a few hundred to several thousand different toxins. Most of them, including the incredibly bio-diverse turrid snails, have never been examined in the laboratory because they are smaller than an inch long and live in areas that are less accessible than the habitats of the shallow water-loving cones. But they, too, are chock full of venom peptides. By that count, there may be anywhere from 300,000 to 30 million different toxic peptides just waiting to be discovered and sequenced. That kind of venomous success is unmatched by any other toxic group.

So how do the venomous snails create so many toxins? Their secret is a genetic advantage: their venom genes are among the fastest-evolving DNA sequences on Earth. We tend to think of evolution by its outward effects: the diversity of traits and behaviours that set each species apart from its closest relatives. But evolution is a measure of genetic change, not physical differentiation. After all, individuals in a species can look very different from one another, but they remain tethered by their genetic makeup. For about a century, scientists have defined evolution as a change in the frequency of gene variations (called *alleles*) in a population. The "rate" or "speed" of evolution, then, refers to how fast genes mutate or duplicate. And when it comes to evolutionary speed, the venomous snails are the Usain Bolts of the animal kingdom. And you thought snails were slow!

Conotoxin genes are among the fastest-duplicating genes on Earth. The A-superfamily conotoxin genes, for example, spontaneously clone themselves, on average, 1.13 times every million years. That's three times as fast as the fastest-duplicating genes from whole-genome studies of other animals, and it's at least twice as fast as the rates for genes renowned for their evolutionary speed, such as the genes which encode our ability to smell. And when scientists looked at just the most recent two million years of cone snail evolution, the rate of duplication was even faster: the A-superfamily conotoxin genes – of which each species possesses dozens – were duplicating at a rate of almost four copies per million years. More importantly, cone snails maintain this high duplication rate, never settling in. No other animal species is known to have such constantly duplicating genes.

These genes don't just duplicate – they also change exceedingly fast. The rate of non-synonymous substitutions in conotoxins is estimated at between 1.7 and 4.8% per million years. That's five times as many mutations as the highest rates reported for mammals, and three times the highest rates found in fruit flies. And that's just the average rate – right after a duplication event, the non-synonymous substitution rate is at least *23% per million years*.

While the cone snails set the bar for speed, many venomous animals have toxin genes that clock in with high evolutionary rates, particularly their neurotoxins. Rapid diversification is the hallmark of many venoms, and this accelerated molecular evolution leads to inconceivable toxin diversity – more toxins than scientists have been able to count, sequence, or study. And yet, venoms from species as disparate as octopuses and snakes converge upon the same targets. The actual molecules in venom are hypervariable, but the functions of those components are markedly conserved.

The drive for evolutionary speed isn't to come up with new targets to attack – it's to ensure that toxins stay potent over time. Neurotoxins, as you can see in the case of the cone snails, are excellent for capturing prey, as causing rapid paralysis is a great way to slow down your potential meal. But the minute a venomous predator starts using a molecule which shuts down its prey's sodium channels, it creates a strong selective pressure in the prey for sodium channels that don't respond to the toxin. Sometimes, all it takes is a few mutations to derail a toxin's activity. Venomous animals must always be prepared to change things up, to throw a curveball and hope that they get a strike – or, as the cone snails do, to throw hundreds of balls at once, making damn sure their prey can't hit them all. "What the snails are doing is the equivalent of combination drug therapy," Toto explained. "They don't just use one drug for a physiological endpoint – they always use multiple components."

CHRISTIE WILCOX is a science writer and biologist based in Hawaii. *Venomous* is her first book.

CREDIT
Adapted from *Venomous: How Earth's Deadliest Creatures Mastered Biochemistry* by Christie Wilcox. Published by Scientific American / Farrar, Straus and Giroux, LLC. 

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# A SECOND CHANCE FOR NUCLEAR POWER?

Cheap, no meltdowns and no bombs: that's why China and the US are collaborating to build a molten-salt reactor. By RICHARD MARTIN.

→

AHEAD OF ITS TIME: A prototype molten-salt reactor operated at the Oak Ridge National Laboratory in the US from 1965 to 1969 before the program fell out of favour.

01

IN FEBRUARY, I flew through the interior of a machine that could represent the future of nuclear power. I was on a virtual-reality tour at the Shanghai Institute of Applied Physics in China, which plans in the next few years to build an experimental reactor whose design makes a meltdown far less likely.

INSIDE THE CORE — a superhot, intensely radioactive place where no human will ever go — the layers of the power plant peeled back before me: the outer vessel of stainless steel, the inner layer of a high-tech alloy, and finally the nuclear fuel itself, tens of thousands of billiard-ball-sized spheres containing particles of radioactive material.

Given unprecedented access to the inner workings of China's advanced nuclear R&D program, I was witnessing a new nuclear technology being born. Through the virtual reactor snaked an intricate system of pipes carrying the fluid that makes this system special: a molten salt that cools the reactor and carries heat to drive a turbine and make electricity. At least in theory, this type of reactor can't suffer the kind of catastrophic failure that happened at Chernobyl and Fukushima, making unnecessary the expensive and redundant safety systems that have driven up the cost of conventional reactors. What's more, the new plants should produce little waste and might even eat up existing nuclear waste. They could run on uranium, which powers 99% of the nuclear power plants in the world, or they could eventually run on thorium, which is cleaner and more abundant. The ultimate goal of the Shanghai Institute: to build a molten-salt reactor that could replace the 1970s-era technology in today's nuclear power plants and help wean China off the coal that fouls the air of Shanghai and Beijing, ushering in an era of cheap, abundant, zero-carbon energy.

Over the next two decades China hopes to build the world's largest nuclear power industry. Plans include as many as 30 new conventional nuclear plants (in addition to the 34 reactors operating today) as well as a variety of next-generation reactors, including thorium molten-salt reactors, high-temperature, gas-cooled reactors (which, like molten-salt reactors, are both highly efficient and inherently safe) and sodium-cooled fast reactors (which can consume spent fuel from conventional reactors to make electricity). Chinese planners want not only to dramatically expand the country's domestic nuclear capacity but also to become the world's leading supplier of nuclear reactors and components, a prospect that many Western observers find alarming.

The Shanghai Institute's effort to develop molten-salt reactors, a technology that has sat all but forgotten in the US for decades, reflects just how daring China's nuclear ambitions are. Already, the government has invested some 2 billion Chinese renminbi (US$300 million) over the past five years in molten-salt R&D. Building actual plants will require tens of billions more. As with other innovative nuclear technologies in development around the world, there are few guarantees. Though people have run small, experimental molten-salt reactors, no one's ever actually built one at utility scale and hooked it up to the grid. Yet the Chinese government expects to have a commercial-size plant up and running within 15 years, helping to revive the beleaguered nuclear power industry.

The first experiments with molten-salt reactors were carried out at Oak Ridge National Laboratory in Tennessee, under its director Alvin Weinberg in the late 1950s. Today's Chinese program, in fact, is the fruit of a unique and somewhat controversial partnership between Oak Ridge and the Shanghai Institute. The US research program went on for more than a decade but was eventually shut down in favour of the technology used in the vast majority of nuclear power plants today. In retrospect, that decision contributed not only to the demise of a promising nuclear technology but also to the long stagnation of the industry.

Today, though, the world needs nuclear energy more than ever if we are to limit climate change. According to the International Energy Agency, the world's nuclear capacity needs to more than double by mid-century if we are to stay within 2 °C of warming. As it stands now, that seems unlikely. Several countries, including China and India, have embarked on massive nuclear power build-outs, but most will entail big, conventional reactors – technology that is too expensive for much of the rest of the world. Even countries such as Germany that can afford nuclear power are phasing it out because they fear another disaster. That makes the fail-safe nuclear power plants being developed at the Shanghai Institute of paramount urgency.

After my virtual tour, Kun Chen, one of the molten-salt program's lead scientists, walked me back to the institute's main administration building. Snow had fallen overnight, and it was bitterly cold. In the auditorium a small crowd of staffers had gathered for a talk by Xu Hongjie, the director of the molten-salt program. It was the week before the lunar new year holiday, and the institute's annual banquet was being held that night. Xu spoke for more than two hours about the history of molten-salt technology and its prospects for the future.

"This has been China's dream for a half-century," he said. "Previously, we lacked the necessary knowledge and skills to make it a reality. Now we have the resources and the technology and the expertise. Now we can do it."

ALVIN WEINBERG FIRST CAME to Oak Ridge in 1945, just after its laboratories had been built in the northern Tennessee hills to make weapons-grade uranium and plutonium. A veteran of the Manhattan Project, Weinberg became director of the rapidly growing national lab in 1955 and held the position until 1973. He was a pioneering nuclear physicist and a philosopher of nuclear power who used the phrase "Faustian bargain" to describe the tension between industrialised society's thirst for abundant energy and the extreme vigilance needed to keep nuclear power safe. To make this energy source both clean and extremely cheap, he believed, the link between nuclear power and nuclear weapons would have to be severed. And the way to break that link was the thorium molten-salt reactor.

Under Weinberg's leadership, a team of enthusiastic young chemists, physicists, and engineers operated a small, experimental molten-salt reactor from 1965 to 1969. That reactor at Oak Ridge ran on uranium; Weinberg's eventual goal was to build one that would run exclusively on thorium, which, unlike uranium, cannot easily be made into a bomb. But the molten-salt experiment was abandoned in the early 1970s. One big reason was that Weinberg managed to alienate his superiors by warning of the dangers of conventional nuclear power at a time when dozens of such reactors were already under construction or in the planning stages.

By the end of the century, the US had built 104 nuclear reactors, but construction of new ones had all but come to a halt and the technology remained stuck in the 1970s. Because conventional reactors require huge, costly containment vessels that can blow up in extreme conditions, and because they use extensive external cooling systems to make sure the solid-fuel core doesn't overheat and cause a runaway reaction leading to a meltdown, they are hugely expensive. Two new reactors being built now in Georgia could cost $21 billion, 50% over the original estimate of $14 billion. All that for 40-year-old technology.

02


Alvin Weinberg's molten-salt reactor was an idea ahead of its time.

Today, though, as climate change accelerates and government officials and scientists seek a nuclear technology without the expensive problems that have stalled the conventional version, molten salt is enjoying a renaissance. Companies such as Terrestrial Energy, Transatomic Power, Moltex, and Flibe Energy are vying to develop new molten-

OVER THE NEXT TWO DECADES, CHINA HOPES TO BUILD THE WORLD'S LARGEST NUCLEAR POWER INDUSTRY.

TODAY, AS CLIMATE CHANGE ACCELERATES AND GOVERNMENT OFFICIALS SEEK A NUCLEAR TECHNOLOGY, MOLTEN SALT IS ENJOYING A RENAISSANCE.

salt reactors. Research programs on various forms of the technology are under way at universities and institutes in Japan, France, Russia and the US, in addition to the one at the Shanghai Institute. Besides the work going into developing solid-fuel reactors that are cooled by molten salt (like the one I toured virtually in Shanghai), there are even more radical designs that also use radioactive materials dissolved in molten salt as the fuel (as Weinberg's experiment did).

Like all nuclear plants, molten-salt reactors excite atoms in a radioactive material to create a controlled chain reaction. The reaction unleashes heat that boils water, creating steam that drives a turbine to generate electricity. Solid-fuel reactors cooled with molten salt can run at higher temperatures than conventional reactors, making them more efficient, and they operate at atmospheric pressures – meaning they do not require expensive vessels of the sort that ruptured at Chernobyl. Molten-salt reactors that use liquid fuel have an even more attractive advantage: when the temperature in the core reaches a certain threshold, the liquid expands, which slows the nuclear reactions and lets the core cool. To take advantage of this property, the reactor is built like a bathtub with a drain plug in the bottom; if the temperature in the core gets too high, the plug melts and the fuel drains into a shielded tank, typically underground, where it is stored safely as it cools. These reactors should be able to tap more of the energy available in radioactive material than conventional ones do. That means they should dramatically reduce the amount of nuclear waste that must be handled and stored.

Because they don't require huge containment structures and need less fuel to produce the same amount of electricity, these reactors are more compact than today's nuclear plants. They could be mass-produced in factories and combined in arrays to form larger power plants.

All of that should make them cheaper to build. Unlike wind and solar, which have gotten far less expensive over time, nuclear plants have become much more so. According to the US Energy Information Administration, the inflation-adjusted cost of building a nuclear plant rose from $1,500 per kilowatt of capacity in the early 1960s to more than $4,000 a kilowatt by the mid-1970s. In its latest calculation in 2013, the EIA found that the figure had risen to more than $5,500 – more expensive than a solar power plant or onshore wind farm and far more than a natural gas plant. That up-front cost is amplified by the large size of the reactors; at the average cited by the EIA, a one-gigawatt plant would cost $5.5 billion, a risky investment for any company.

Those up-front costs are balanced by the fact that nuclear plants are relatively cheap to operate: at new plants the levelised cost of electricity, which measures the cost of power generated over the lifetime of the plant, is $95 per megawatt-hour, according to the EIA – comparable to the cost of electricity from coal-fired plants, and less than solar power ($125 a megawatt-hour). Still, natural gas plants are far cheaper to build, and the cost of the electricity they produce ($75 a megawatt-hour, according to the EIA) is also lower. Tightening regulations on carbon emissions makes nuclear more attractive, but lowering the cost of construction is critical to the future of zero-carbon nuclear power.

That is the pitch being made by a new crop of startups working on advanced nuclear reactors, several of them funded by Silicon Valley investors. Transatomic Power, for instance, was founded by a pair of MIT PhDs, Leslie Dewan and Mark Massie, who have designed a 520-megawatt plant (about the size of an average coal plant today) that they think can be built for $2 billion, or $3,846 per kilowatt of capacity. That is in line with the cost of building a solar power plant – but would have the huge advantage of being able to produce power continuously, not just when the sun shines. Terrestrial Energy, which recently won a research grant from the Canadian government to build a prototype reactor, says that its molten-salt reactor could eventually be built for as little as $2,000 a kilowatt.

But even though molten-salt designs have energised inventive young technologists, getting a novel nuclear power technology licensed and built in the US remains a daunting prospect. Simply applying for a licence from the Nuclear Regulatory Commission can take years and cost hundreds of millions of dollars, which is why some of these startups may never get off the ground. What's more, even $2 billion would be a lot of money for investors and utilities to spend on an unproved technology with questionable financial advantages. Which is why the program closest to producing a working reactor is in the People's Republic of China.

EVEN AS THE ORIGINAL EXPERIMENT with molten-salt technology was winding down in the US in the 1970s, a small group of researchers at the Shanghai Institute of Applied Physics, part of the Chinese Academy of Sciences, was launching its own investigation into thorium-fuelled molten-salt reactors. But China, which would not start up its first nuclear power plant until 1991, lacked the expertise and the money to develop the sophisticated machinery and expensive materials in advanced reactors. By the 21st century, like all other countries with nuclear power, China relied on conventional reactors. But the embers of the concept still glowed in the minds of Chinese nuclear scientists.

From the Chinese point of view, thorium has a particular advantage: while mainland China has a small percentage of the world's uranium, it has plenty of thorium. Having an abundant source of carbon-free energy would solve several of China's energy dilemmas at one go.

"In the eyes of the central government, we are not here to do mature technologies – we have to create something new, something strategic," says Kun Chen, the molten-salt scientist who led my virtual tour in Shanghai. "You have to think big."

Educated at the prestigious University of Science and Technology of China in Hefei, Chen earned a PhD from Indiana University and worked for several years at Argonne National Laboratory (which, like Oak Ridge, is part of the US Department of Energy). But he came back to China to build a world-changing reactor. He heard about it in 2009, when he visited Shanghai to present a seminar at the Institute of Applied Physics. A scientist there told him about the thorium molten-salt reactor – a project not yet funded or announced.

"Our team got most of the technical documents from the web – they were posted by the Oak Ridge team," recalls Xu Hongjie, the director of the molten-salt program, shaking his head in either admiration or amazement at the openness of the Americans. "They posted everything there for free."

At Xu's urging, Chen joined the Shanghai Institute in 2010, and today he is in charge of collaborating with Oak Ridge. The US lab is contributing research on materials, control systems and computer simulations to the project and has built a large molten-salt testing facility that was funded by the Chinese Academy of Sciences. While some scientists and nuclear-power advocates vehemently oppose the idea of helping China build a world-leading nuclear industry, many Oak Ridge engineers are just eager to see molten-salt reactors built somewhere. "One of the important things to realise is that a number of key people in molten-salt reactors are retiring very fast or passing away," says David Holcomb, who heads Oak Ridge's collaboration with the Shanghai Institute. "You can't just import a new set of staff if we're going to maintain this capability. China is providing the funding that allows us to transfer that knowledge, to gain practical experience at building and operating these reactors."

To start, the Shanghai Institute plans to take a hybrid approach, using molten salt to cool a solid-fuel core similar to the ones in conventional nuclear plants. Then, Chen says, the team will progress to liquid fuels to fully realise the technology's potential for safety and efficiency. At first the fuel will be uranium, but the Chinese engineers plan to shift later to thorium.

The timelines are aggressive, at least by the standards of the nuclear industry. The Shanghai Institute aims to start up a commercial-scale, solid-fuel plant by 2030 and a 100-megawatt demonstration liquid-fuel reactor by 2035. Much of the current work, Chen told me, focuses on solving the complex plumbing challenges associated with the highly corrosive molten salt. I was struck by the confidence and idealism of the young scientists working at the institute – an optimism not seen in US nuclear circles since Weinberg's day.

On my last day in Shanghai, Kun Chen and I strolled around the institute's grounds. The snow was mostly gone, but the icy wind was still sharp. He showed me the campus's latest construction project: a three-storey, warehouse-sized building to house the thorium molten-salt program. All the chemistry labs, machine shops, computers, offices and the test loops and pumps and prototypes, will be housed here when the building opens later this year. It was just a shell at the time, but it was a symbol of China's commitment to the next nuclear era. The dream of American scientists at Oak Ridge, a half-century ago, is taking shape here, thousands of kilometres away.

RICHARD MARTIN is the senior editor for energy at *MIT Technology Review* and author of *Coal Wars: The Future of Energy & The Fate of the Planet*.



IMAGES
01 Oak Ridge National Laboratory
02 Oak Ridge National Laboratory

# CRACKING THE SECRETS OF STALAGMITES

Pauline Treble dives into Australia's caves to understand climate – past, present and future. SARAH SCOLES reports.

→

PAULINE TREBLE pores over stalagmite sections at the Australian Nuclear Science and Technology Organisation.

01

**INSIDE MOONDYNE CAVE**, on the southwest coast of Western Australia, stalactites hang in clusters from the ceiling – delicate crystal straws resting alongside stout organ pipes. Tapered stalagmites rise like pointy hats from the cave floor.

GOING JUST A FEW CENTIMETRES INTO THE STRUCTURE TRANSPORTS YOU FAR BACK IN TIME.

**IN THE EARLY 20TH CENTURY**, Moondyne's ghostly structures attracted enough tourists that, in 1911, cave managers installed a boardwalk to control the flow of people through the cave. In 1992, a local tour company ripped up the rotting old wooden boardwalk to replace it with new timber. In the decommissioning, workers found a stalagmite about the size of a standard paper clip sprouting from a piece of the old wood. They shelved the odd little souvenir, thinking maybe someday it would be of use.

They were right. In 2001, a doctoral student from Australia National University named Pauline Treble visited several caves in Western Australia looking for research samples. Treble thought of herself as an underground detective. A palaeoclimatologist, she was studying caves as a way of reconstructing Earth's past.

A cave management employee pulled out the Moondyne splinter with its conjoined stalagmite. "Is this of any interest to you?" he asked.

Treble's eyes gleamed as she realised how special this stalagmite was. It was a cipher that could reveal how 20th-century climate had encoded itself in the formation of this hunk of mineral.

Moondyne would alter the course not just of Treble's project, but of her entire field.

**CAVES STORE** permanent records of temperature and rainfall patterns. Rainwater filters through the ground, drips into the cave and evaporates, depositing minerals. Gradually, stalactites and stalagmites – collectively known as speleothems – build up in layers, like the drip castles kids construct at beaches. The outside of each one is modern. But going just a few centimetres into the structure transports you far back in time. "These speleothems just sit here, quietly dripping away for thousands of years in the dark, silent witness to these climate and environmental changes going on around them," says Treble.

Coaxing climatic history out of those silent witnesses depends on knowing exactly how far back in time a given layer goes. Scientists figure out the age of speleothem samples using radioactive dating, usually on the uranium that seeps into them as they grow. As uranium ages, it decays, at a regular and predictable rate, into thorium. By measuring how much uranium remains in a given speleothem relative to how much thorium has appeared, scientists can learn how old the sample is.

The trouble is that radioactive dating is inherently fuzzy. Researchers can only approximate the age of a cave deposit to within about 100 years. That's why the boardwalk speleothem was so valuable. Treble knew when it had first started to grow – the boardwalk's 1911 grand opening was a kind of birth certificate – and she had its RIP date too: 1992 when the boardwalk was torn up.

Treble could now check to see how well the known environmental conditions between 1911 and 1992 matched up with the speleothem's chemical composition. She could determine whether – and if so, how – speleothems encrypted information about rainfall and climate.

In the years since she stumbled on her boardwalk barnacle, Treble – now a research scientist at the Australian Nuclear Science and Technology Organisation – has become a pre-eminent cave palaeoclimatologist. Leading some of the world's longest-running cave monitoring programs, she's deduced how historical climate changes have affected rainfall in Australia and the transformations future climate change is likely to bring. Her methods have also helped set a course for cave researchers examining shifting climates elsewhere in the world.

02

The stalactites and stalagmites of Moondyne cave hold crucial clues to Western Australia's past climate.

TREBLE WAS A CURIOUS KID, and not unlike a cave herself: she observed, absorbed and interpreted the environment around her. She still does in her work and her hobby. When she's not playing with her data or kids, she paints. She's just had her first exhibition – portraits of her children, aged seven and nine – and has moved on to still life.

"To reproduce a vase is all about careful, careful observation," she says. "That's the same with science; it's not about going in with a biased idea of how the world should work."

Treble wasn't always so keen on caves. When she was a child, her older brother was into spelunking. Seeing photographs of him on underground adventures, she thought: "That would be terrifying." The idea of going beneath Earth's surface held no appeal. She did, though, discover a taste for climbing rocks – scaling high cliffs wasn't nearly as scary as venturing underground.

At the University of Sydney, Treble started out in chemical engineering. But when she discovered the geography department, she was hooked. She was fascinated by the idea that it was possible to reconstruct the planet's past climate. When a professor showed her two Tasmanian speleothems and suggested she could use them to look for evidence of ice ages, her future was clinched.

Working with the Tasmanian speleothems led Treble underground for the first time. There, her childhood fear disappeared. Here was a fairy land of wall-to-wall crystal and stalagmites so big they resemble fossilised trees. Beneath the Earth's surface, Treble felt safe.

And she liked getting to know a hidden part of the planet – her artist's eye eager to see the world beyond its surface level.

WHILE CAVES ARE GERIATRIC, cave palaeoclimatology is just a Gen-Xer, born in 1968 when New Zealand palaeoclimatologists Chris Hendy and Alexander Thomas Wilson published the first cave decoder manual, outlining how scientists could trace the history of surface climate from underground. "At the time, there were very few terrestrial records you could reconstruct," says Treble. Tree rings tell some of the story, but trees are seldom old on a geologic time scale. Ice cores are old but primarily come from Earth's far north and south. Caves, though – caves are everywhere, and their insides are both very changeable and very, very old.

Speleothems encode information about the water that begat them. We think of water as having a straightforward formula: two hydrogen atoms and one oxygen atom. But in rainwater, oxygen normally comes in two main forms: isotopes that carry either 16 or 18 neutrons, like twins with slightly different weights. Generally, when the world is cooler, rain contains more light oxygen-16 relative to heavy oxygen-18. When it's warmer, oxygen-18 catches up.

As Hendy and Wilson explained, that relationship between temperature and water chemistry meant that scientists could reconstruct the history of a region's temperature fluctuations by using speleothems. If modern temperatures were shifting in a way that was out of proportion with past fluctuations, that most likely indicated a human cause.

Hendy and Wilson's approach opened up a new era of climate research. Now, scientists at sites all over the world could piece together clues from right beneath their feet to better understand how the world once was and what it might become.

03

A stalagmite records seasonal rainfall variations via the ratio of oxygen isotopes in its layers. Pauline Treble's work decoded details of this relationship.

Eventually, though, it became clear that Hendy and Wilson's model was incomplete. It assumed that the only factor that changed water's oxygen isotope composition was temperature. But other factors, researchers were discovering, also affected oxygen isotopes. As air masses move inland, for example, they lose comparatively more heavy oxygen, and the rain they drop reflects that. The same thing happens as weather systems move toward more extreme latitudes.

By the late 1990s, Treble says, researchers suspected that speleothems "are actually archives of past rainfall, rather than temperature". When more rain falls, the amount of oxygen-18 compared to oxygen-16 also falls. In dry periods, heavy oxygen makes a comeback. But just how those shifts affected the makeup of speleothems was largely theoretical. Moondyne's boardwalk speleothem gave Treble a chance to test the theory against real rainfall patterns.

Western Australia, the stalagmite's home region, had seen a 15% decrease in rainfall between 1970 and the early 2000s. Now Treble could test whether that dry period was reflected, year for year, in her speleothem's shifting oxygen isotopes It was an opportunity not to be missed.

*Stop – drop everything*, she told herself. *Focus on this*.

In the Moondyne speleothem's layers, she found clear evidence of annual cycles: different trace metals deposited with predictable regularity as the calendar flipped forward. She could match the passing seasons to the chemicals' shifting concentrations, like matching a stack of photos to the dates they were taken by looking at clues such as snow on the ground, freshly mown grass and autumn leaves. In speleothems, the clues came from trace elements such as magnesium, sodium and barium which change with the seasons. And in the season-subdivided speleothem, she could detect more of the heavy oxygen appearing when the dry period began in the 1970s. Sure enough, it steadily rose as more precipitation fell.

Treble recapitulates that moment. "Yes, here it is!" she says, throwing her fist through the air. *Victory!* Her real-world observations backed an idea that until then had existed mostly on paper.

She became the envy of her young colleagues who were struggling to find samples. At one conference after she presented her work, another student approached her.

"That's my PhD," he said, visibly dejected. "That's what I've been trying to do."

"Oh, well," said Treble. Bad luck.

BECAUSE ACADEMIC POSITIONS in her field were scarce in Australia, in 2003 Treble accepted a post-doc at the University of California, Los Angeles. But she always longed to return home. "In my heart, I knew I had this great story for the southwest of Western Australia," she says. "There's just no palaeo records for that region, and it was just dying to be done."

That story, which she has continued to investigate ever since, was about how the westerly winds have evolved over the millennia and what effect that has had on Western Australia's water supply. The westerlies are responsible for what little precipitation Western Australia gets. But since around 1970, these winds have shifted southward, taking the rain clouds with them.

Scientists believe a number of factors have contributed to the westerlies' migration, says Treble. Some of the variability is likely natural, and ozone depletion around Antarctica has also probably played a role, she says. Scientists also theorise that the westerlies are sensitive to increases in greenhouse gases, whose concentrations in the atmosphere continue to mount. Just how sensitive, though, is an open question.

Treble's work in Western Australia's caves is premised on the idea that if she can figure out just how changeable rainfall was throughout the region's history – as reflected in speleothems – then she can deduce how big an effect climatic changes have on the westerlies. That information could help shape forecasts for how life in Western Australia might alter in the coming decades: how little winter water crops will get, for example, and how much the water supply to nearby Perth could dwindle. It can also feed into the climate models other scientists use to forecast future climatic shifts.

Even while she was still in California, Treble believed such work could also make climate change real for people back home, by revealing how a global and long-term process is playing out in the here and now. "This is one of the current problems with people struggling to understand the impact of climate change on their lives," says Treble. "They're only seeing climate or rainfall through one lifetime. They don't have an appreciation of how much things could change." But caves hold the whole history of those changes within themselves, if only she could decode it. She began writing grants to return home.

In 2005, with a grant from Land and Water Australia, Treble set up what would become one of the world's longest cave-monitoring programs. The rocky formations are to past climates what the Rosetta Stone was to deciphering hieroglyphics: Treble and colleagues can look for the seasonal and climatic signatures in older speleothem samples and understand when it rained and how hard, and so how far the westerlies wandered back then.

Her most extensive monitoring operation is in a cave called Golgotha, about 20 kilometres north of Moondyne. Caves in this area lie beneath native vegetation, rather than agricultural fields or private properties. That means Treble can study how caves such as Golgotha respond chemically to

TREBLE ALWAYS BELIEVED HER WORK COULD MAKE CLIMATE CHANGE REAL FOR PEOPLE BACK HOME.

climate change in the absence of other human-made environmental influences.

What's more, water penetrates the porous rock in the region easily, building speleothems up quickly and packing them with information about the recent world above. Treble's team is currently reconstructing the past 8,000 years of rainfall, to build that baseline of how the rainfall and the westerlies have evolved long-term, how the current dry period compares, and what future shifts in the wind might mean for Western Australia.

TREBLE'S TEAM IS CURRENTLY RECREATING 8,000 YEARS OF RAINFALL.

INSIDE GOLGOTHA, Treble's equipment is a constant presence, as much as the otherworldly stalactites and stalagmites that carry the cave's story. The site is a five-hour flight from Treble's home base near Sydney, and she only makes the trip there about once a year. Anne Wood and Elizabeth McGuire of the Department of Parks and Wildlife make sure the day-to-day data keep coming. When Treble does scramble into the cave, wearing full-body coveralls, her brown hair tied back and a lamp beaming from her forehead, there is a military focus about her. Her collaborator Ian Fairchild at the University of Birmingham remembers a 10-day field trip he once took with Treble. The experience was intense. "Pauline is a bit of a stickler," Fairchild says. "We had to work every day, and there were no stops. We were allowed some wine, I think, at the end of the day on the last day."

He means "stickler" in a nice way. "Pauline is certainly a careful scientist – very methodical, very high ethical values," he says. Where others have cut bureaucratic corners, she sticks to the book – monitoring drip sites for years to figure out which will be most scientifically useful, sending regulators documentation along the way and waiting for permission before taking physical samples. That quality, Fairchild says, has helped keep her in the good graces of the land management agencies that hold the keys to the underground castles.

The massive Golgotha dataset also attracts scientists with different interests. Some geostatisticians from the University of Lausanne and Western Sydney University recently offered to use lasers to make a 3-D map of Golgotha's water paths. Treble pounced on the opportunity.

The map led to an important discovery: where tree roots have cracked rock at the surface, rainwater funnels into the cave below. But those same roots then change the composition of the water, sucking up nutrients – including the same trace metals that palaeoclimatologists use as climate clues. If an oak tree happens to be growing directly above a speleothem, that scrambles the story. And unscrambling, as with an egg, isn't really possible. That, Treble realised, means it's crucial to find speleothems that are free of such blemishes.

Tree roots aren't the only force of nature that can skew cave readings, as Treble's group recently discovered. Taking readings at a different Western Australian cave called Yonderup, Treble couldn't see the oxygen signature of the rainfall changes she knew had occurred between 2005 and 2011.

She shelved the Yonderup data, figuring the samples must have become contaminated – although by what, she didn't know. But she did have a suspicion: a fire had burned above Yonderup in 2005. Somehow that fire must have affected the development of the cave formations. But how?

She didn't get an answer until a few years later when a University of New South Wales geoscience student, Gurinder Nagra, approached her and collaborator, Andy Baker, in need of a project. They put the budding cave detective to work finding out how the fire had affected the water flows.

Nagra, with help from others in Treble and Baker's group, discovered that when a fire burns above a cave, water evaporates at a higher rate. In response, the cave's heavy oxygen rises in a way that is – so far –indistinguishable from the increase due to rainfall changes. Cave sites that have sat silent under conflagrations, then, provide a blemished picture of climate.

When scientists don't know these imperfections exist, Treble says, they see the data as smooth and simple: temperature changes affect water chemistry – the end.

Treble has helped reveal just how many warts there are in the data. Her science imitates her art.

By revealing the caves' imperfections, she has forced her field towards greater realism, just as detailing people's blemishes and hairs, makes them more human. Embracing this increasingly gritty portrait of caves, Treble plans to keep probing speleothems to read the past, put the present in context and help predict the future.

SARAH SCOLES is a science writer based in Denver, Colorado, US. Her biography of astronomer Jill Tarter, *Making Contact*, will be published next year.

IMAGES
01 Paul Robbins / Monde Photo
02 Peter Bell
03 Pauline Treble

PEOPLE, CULTURE
& REVIEWS

# SPECTRUM

ZEITGEIST

## Old media's place in the internet age

Celebrated science documentary maker Sonya Pemberton is inspired by the new offerings that have sprung up on YouTube and Facebook. ANDREW MASTERSON reports. →

01

ZEITGEIST

# Old media's place in the internet age

→ Since its release in mid-2015, *Uranium: Twisting the Dragon's Tail*, a three-part documentary made by Melbourne's Genepool Productions, has gathered a swag of distinctions – some more welcome than others.

In September this year, the show, written by Wain Fimeri and presented by Derek Muller, won the gong for Best Long Form Series at the prestigious Jackson Hole Science Media Awards held in Boston. After it was broadcast in the US, however, the production achieved another milestone.

"It became the most illegally downloaded film in PBS International's history," says Genepool founder and creative director, Sonya Pemberton. "It's a dubious honour."

But to Pemberton, it was an indication that the world of traditional science documentary-makers and the upstart community of new-breed, internet-based science communicators were nowhere near as far apart as commonly thought.

IT BECAME THE MOST ILLEGALLY DOWNLOADED FILM IN PBS INTERNATIONAL'S HISTORY

In one important sense, *Uranium* had a foot in both camps. Commissioned and made as broadcast television, the three-parter was presented by Canadian-Australian host Muller, who is best known for presenting short, sharp science videos on his own YouTube channel, Veritasium.

The channel boasts just shy of four million subscribers. Cross-promotion of *Uranium* between Veritasium, traditional broadcasters and the Facebook phenomenon I F---ing Love Science (with 25 million fans) resulted in unprecedented levels of awareness for Pemberton's product.

It also resulted in unprecedented levels of theft. This was not so much a problem, she says, as an opportunity. "I'm sure some people are not happy about it and I'm sure we've lost quite a lot of sales because of that, but in terms of encompassing new media I think it speaks for itself," she notes.

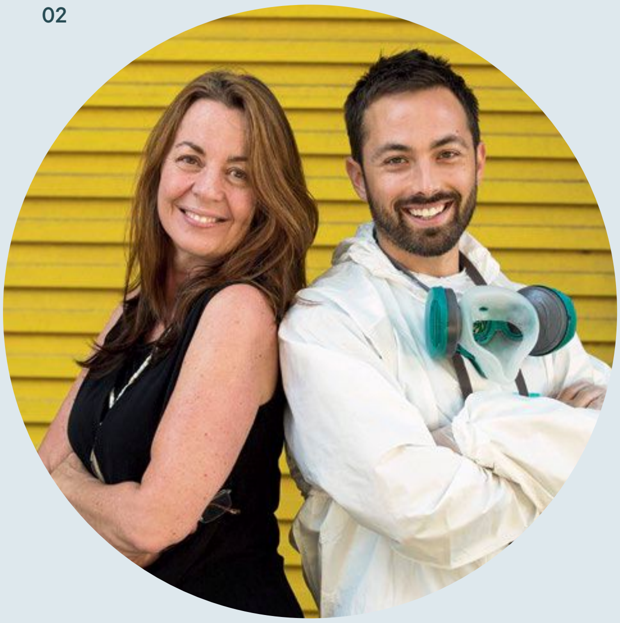
"The trick now is to learn from what we discovered and apply it to the next shows. You don't leave that [internet] audience feeling left behind. They wanted the film and they wanted it right now – they didn't want to wait until next week."

The experience represents the latest in a long series of learning opportunities for Melbourne-based Pemberton, who has been making science-based television for 28 years. After graduating from university with a degree in film and television, she started her career in drama, rising quickly to the position of first assistant director on a number of shows. On one of these, a series called *Adventures on Kythera*, she met cinematographer Harry Panagiotidis, now her husband.

Panagiotidis has credits on more than 40 Australian and international feature films. He has filmed many – and co-produced all – of Genepool's documentaries.

After a couple of years, Pemberton – a doctor's daughter and epidemiologist's granddaughter who had long been fascinated by science – took a sharp left turn and joined the CSIRO as a filmmaker. There she made 21 films, mostly for use in veterinary science training. It was a period, she says, characterised by filming "animals with ghastly diseases", but which also provided invaluable training and insights.

02



Collaborators: Sonya Pemberton and Derek Muller.

"I was taught by scientists how to communicate science," she says. "I brought the creative side of things, but they taught me how to take a proper analytic approach to the material and how to communicate science to scientists."

Stints with the ABC and the BBC followed before she struck out on her own as an independent science doco-maker.

When she first moved away from drama, many of her peers thought she was making a mistake.

Taking unconventional choices, though, seems to be something of a recurrent theme in Pemberton's career.

In 2004, she was approached by the ABC to look after the science program *Catalyst*, and from there rapidly found herself promoted to the powerful (if awkwardly titled) Head of Specialist Factual. The elevation made her one of the most powerful people in Australian television, but after three years at Aunty's HQ in Ultimo, Sydney she opted to head back to Melbourne.

Again, some observers thought this to be a strange decision, but she has never regretted it. In part, she upped sticks because she was missing her family but the move was also motivated by professional concerns.

"I loved having the potential to fund other people's work," she says, "But I missed making science films. It suits my temperament to be able to think deeply about every frame, every word of a film, and when you're in a commissioning role you just can't do that."

A few years ago she entered into a joint venture with Australia's largest independent television house, Cordell Jigsaw Zapruder, and Genepool Productions was born. The company has since produced a raft of startling and acclaimed documentaries, including *Jabbed: Love, Fear and Vaccines* (which, titled *Vaccines: Calling the Shots*, picked up the Jackson Hole Award for Best Science Journalism); a three-part miscellany called *Tales of the Unexpected*; a documentary about the science of ageing, *Immortal*; and *Catching Cancer*, a revealing look at the role of bacteria and viruses in the aetiology of cancers.

Along the way, Pemberton and her collaborators have been awarded a huge haul of accolades, including an Emmy. Pemberton has been declared Health Journalist of the Year twice and picked up an unprecedented five Eureka Awards for science journalism.

Despite the widespread doom and gloom concerning the decline and division of contemporary media, and the tendency of some political leaders to ditch science fact for fiction, Pemberton remains extremely optimistic about the potential for science television documentaries.

The key, she says, is in finding ways to engage constructively with short-form, online successes such as Veritasium and IFL Science. "This is about shared communities and generating scientific curiosity," she says.

Her association with Derek Muller continues, and she communicates often with IFL Science creator Elise Andrew. There are, she says, many points of convergent interest between the broadcast and internet science realms.

"So what they are interested in is how we as documentary filmmakers sustain an audience for 30, 60 or 90 minutes, and what I'm interested in is their reach, their millions of subscribers," she says.

03

Sonya Pemberton and cameraman husband Harry Panagiotidis on location.

"They are different kinds of modalities, thinking about science communication, and I don't think they are mutually exclusive – and nor do I feel in the slightest bit threatened or nervous about it. I see the challenge as working with them, to be able to do the deep dive and long-form in ways that mean we can collaborate."

Pemberton believes there are a number of critical intellectual and ethical values that are common to all decent science communication, regardless of medium. Integrity matters. Bias must be constantly checked. Brevity is key, and, above all, the result must be useful.

"I think of myself as a curiosity entrepreneur sometimes. What I'm trying to do is get people interested in science – and these people are already doing it, and doing it really well with the younger demographic and reaching widely," she says.

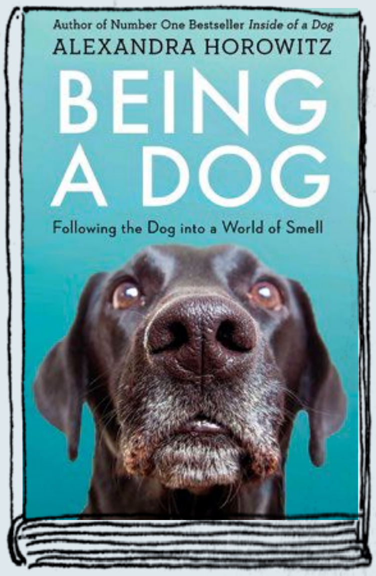
"Young people perceive what we do as 'old school', and so they should. It's entirely appropriate that we should be regarded as old media. But there's nothing wrong with books – and that's also old media."

ANDREW MASTERSON is an author and journalist based in Melbourne, Australia.

IMAGES
01 Simon Schluter / Fairfax Syndication
02 Harry Panagiotidis / Genepool Productions Pty Ltd
03 Martin Kier / Genepool Productions Pty Ltd

REVIEWS

# A new way of seeing the world




NON-FICTION
Being a Dog: Following the Dog Into a World of Smell
by ALEXANDRA HOROWITZ

*Simon & Schuster (2016)*
*RRP $32.99*

AS GROUCHO MARX would have it, "outside of a dog, a book is a man's best friend. Inside of a dog it's too dark to read".

But it is to those insides that Alexandra Horowitz takes us to find out just how man's best friend ticks – and in the process provides a bravura demonstration of two of the most vexed concepts of biology: "biosemiotics" and "umwelt".

To call Horowitz a dog person would be a serious understatement. She is a researcher in dog cognition at Barnard College in New York, where she has taught since 2004. She is also the director of the Horowitz Dog Cognition Lab, which looks into the thinking behind such things as dog-human play, the validity of anthropomorphism, be it of the dog's understanding of "fairness", or an analysis of the "guilty look" Fido will assume when caught chewing the rug.

But dog research is more than a day job to her. She is clearly obsessed by the animals – both her own dogs (Finnegan and Upton) as well as the species in general.

Her previous excursion into viewing the world from a dog's perspective for the lay reader, *Inside a Dog*, made it to the top of every bestseller list and stayed there for weeks, a testament to our enduring fascination with the animals – the only ones, incidentally, that will look we humans in the eye.

Doggie she may be, but Horowitz's view is unsentimental, and she and her research are dedicated to reminding us that, no matter how close a bond we may feel to our companions, they remain at all times a separate species with their own responses, reasoning and values.

Combining her own experiences of canine behaviour in civilian life, as it were, along with lab experiments (her own and others'), Horowitz painstakingly builds us a picture of the world of the dog – its "umwelt" – and a compelling view of how the animals might communicate with each other and the world at large.

Horowitz introduced us to the concept of Uexküllian umwelt in her earlier book but *Being a Dog* takes us a great deal further, attempting to recreate the world through a dog's nose.

The word Umwelt, with a capital U, means environment in German. But German biologist Jakob Johann Baron von Uexküll coined it to mean something more: the total environment that surrounds an organism, not just in the immediate vicinity, but as far as the creature's perception can reach.

While the field of study later found favour with biologists, it was the philosophers who were the earlier adopters, attracted to the concepts for which they found useful application in philosophy of mind. Uexküll's idea of the umwelt, for example, plays a central role in Martin Heidegger's major work *Being and Time*, published in 1927.

As professor at the University of Hamburg in the 1920s, Uexküll founded the Institut für Umweltforschung. He was fascinated by how umwelt worked and, by extension, how living creatures could use their environments to signal intentions and messages to other living creatures – the field we now know as biosemiotics or, when dealing solely with animals, zoosemiotics.

Uexküll concluded that each viewpoint was species-specific and quite unlike the Darwinian concept of an environment that exists objectively and to which organisms adapt. Rather it is a "world in itself", highly subjective and based all but solely on the organism's mode of sensory perception.

HOROWITZ URGES US TO HAVE FAITH IN OUR OWN NOSE – FEEBLE THOUGH THEY MAY APPEAR BY COMPARISON

In the dog, that sensory perception overwhelmingly relies on smell – and it is with the business of the dog's nose that this book is largely concerned.

Horowitz takes exploration of the dog's umwelt to a new level – even so far as kneeling beside a tree in New York to sniff where her mutt Finnegan had just sniffed in order to see the world from his point of view.

After explaining the science behind the dog's truly remarkable sense of smell, Horowitz urges us to have faith in our own nose – feeble though they may appear by comparison.

While our noses might lack the same canine superpowers, Horowitz believes we can still put them to better use than we do. In fact, it is neglect that has led to a loss of our powers, she argues, stating that a dog's world of scents "is rich in a way we humans once knew about, once acted on, but have since neglected".

She joins an art project to create "smellscapes" of cities, hoping to learn a new way of "seeing" a place, partly to develop her own skills and partly to think more like a dog.

Along the way, Horowitz delivers a wealth of interesting insights into being a dog. She debunks, for example, the belief that dogs are "marking their territory" by peeing on trees. If this represented the scope of their "ownership", it would clearly lead to vast and random territorial claims.

Rather, she argues, it is a semiotic device, explaining to all who would smell, who the dogs are, their sex and health status and perhaps a raft of other personal information we can only guess at.

Smells can also provide the dog with insights into the world around it – the rising odours from the earth can signify lower atmospheric pressure and the imminent onset of rain, for example.

Similarly, a wagging tail can tell a story – and not just of friendship. Like scratching the ground after a poop, to release and spread scents from their paw pads, wagging a tail can help spread the unique essence of dog, so important to the animal's signalling to others.

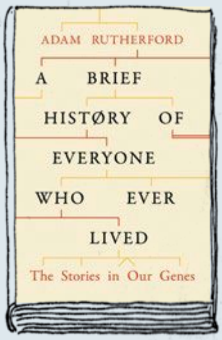
We learn a wealth of factoids, including why a dog licks and why male dogs will greet others by sniffing the tail area and females the face.

Horowitz even moves from amateur to professional canine sniffers – the drug and explosive detection dogs and those that can nose out the scent of cancer in humans.

This is a great book whether you are into dogs or not. It's funny, engaging, at times charming and always thought-provoking. By the end, Horowitz will have you smelling the world in a way you never thought possible – bringing out your inner dog.

— BILL CONDIE

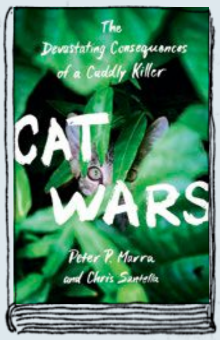
HOLIDAY READING




NON-FICTION
A Brief History of Everyone who Ever Lived
by ADAM RUTHERFORD

*W&N (2016)*
*RRP $32.95*

IF YOU EVER THINK of the human race as a linear "family tree", think again. If you were to work on the idea that your two parents had four parents, who had eight parents, by the time you reach the eighth century you have 137,438,953,472 individuals – more people than have ever existed in total on the planet. That is the premise of the stories in our genes, which set out to untangle the vast inter-related network that is the story of the human race and in doing so rewrite world history – fascinating if sometimes bewildering in scale and concept.




NON-FICTION
Cat Wars
by PETER P. MARRA and CHRIS SANTELLA

*Princeton University Press (2016)*
*RRP US$24.95*

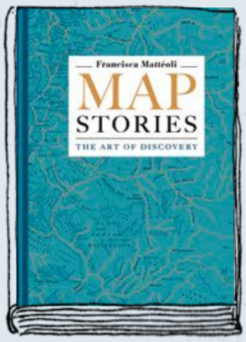
IN 1894, a lighthouse keeper named David Lyall arrived on Stephens Island off New Zealand with a cat named Tibbles. In just over a year, the Stephens Island Wren, a rare bird endemic to the island, was extinct. *Cat Wars* looks at the problem of free-ranging cats that kill billions of wild animals, not to mention the risks to human health, from rabies to the parasitic *Toxoplasma*. It's not an anti-cat book but a level-headed response to a complex and often emotional problem.


NON-FICTION
The Doctor
by KARL KRUSZELNICKI

*Macmillan Australia (2016)*
*RRP $34.99*

NO INTRODUCTION IS NEEDED for Karl Kruszelnicki, of course. Among other topics, the latest book from the prolific science communicator and populariser looks at the "wibbly-wobbly" theories of time travel, discovers how much alcohol makes you speak more loudly, investigates the possibilities of Bitcoin, explains why Americans are no longer the tallest people on Earth and imagines what the detection of gravitational waves will do for you.

REVIEWS




NON-FICTION
Map Stories: The Art of Discovery by FRANCISCA MATTÉOLI

*Hachette Australia (2016)*
*RRP $55.00*

AH, MAPS! They're the way we used to find our way around, you know, before there was Siri to pass on directions from Google for us.

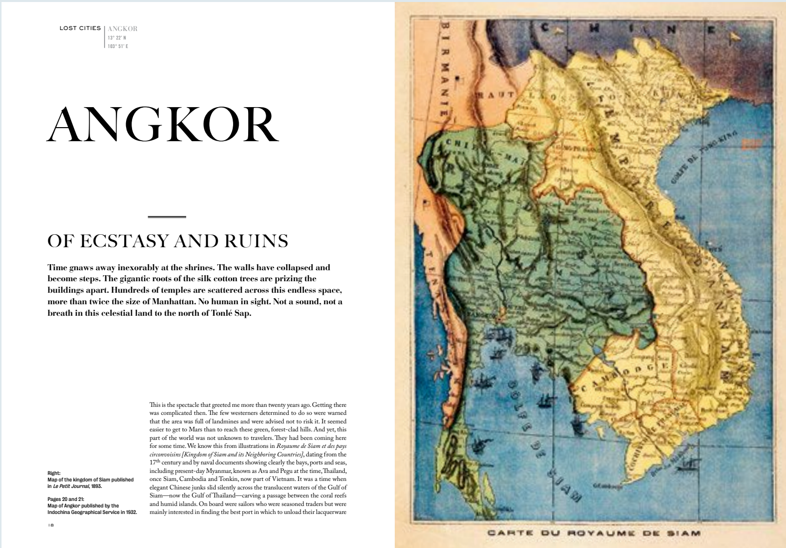
This book tells us two things. First, that maps are already looking like distinctly old technology but, second, they are still such beautiful objects in themselves and packed with romance and possibility in a way that their online counterparts are not.

Francisca Mattéoli presents historic charts as an invitation to the reader on a journey, from map to map, letting our imaginations run free. She has based the experience on her own, as a child, when her grandfather spread out a map of her native Chile.

She came to see maps not as geography but as a treasury of stories, to be opened as we would a novel.

With a map, she says, anything is possible.

— BILL CONDIE


LOST CITIES | ANGKOR

ANGKOR

OF ECSTASY AND RUINS

**Time gnaws away inexorably at the shrines. The walls have collapsed and become steps. The gigantic roots of the silk cotton trees are prizing the buildings apart. Hundreds of temples are scattered across this endless space, more than twice the size of Manhattan. No human in sight. Not a sound, not a breath in this celestial land to the north of Tonlé Sap.**

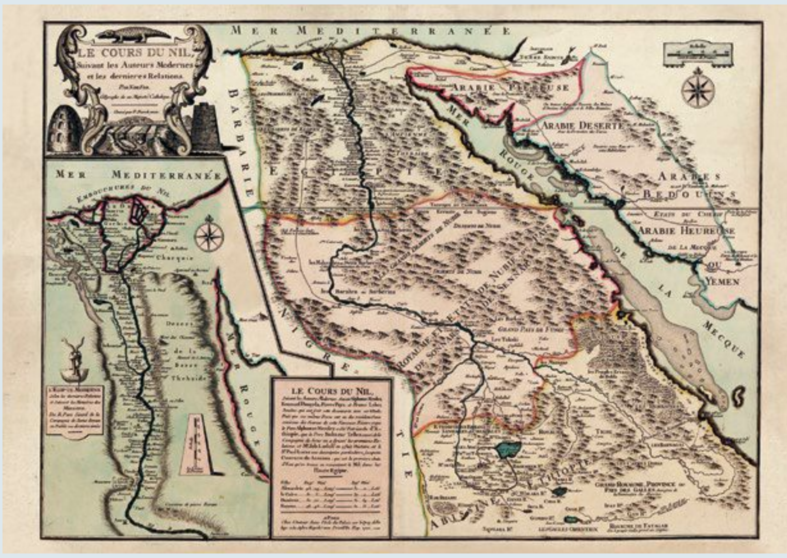
This is the spectacle that greeted me more than twenty years ago. Getting there was complicated then. The few westerners determined to do so were warned that the area was full of landmines and were advised not to risk it. It seemed easier to get to Mars than to reach these green, forest-clad hills. And yet, this part of the world was not unknown to travelers. They had been coming here for some time. We know this from illustrations in *Royaume de Siam et des pays circonvoisins [Kingdom of Siam and its Neighboring Countries]*, dating from the $17^{\text{th}}$ century and by naval documents showing clearly the bays, ports and seas, including present-day Myanmar, known as Ava and Pegu at the time, Thailand, once Siam, Cambodia and Tonkin, now part of Vietnam. It was a time when elegant Chinese junks slid silently across the translucent waters of the Gulf of Siam—now the Gulf of Thailand—carving a passage between the coral reefs and humid islands. On board were sailors who were seasoned traders but were mainly interested in finding the best port in which to unload their lacquerware

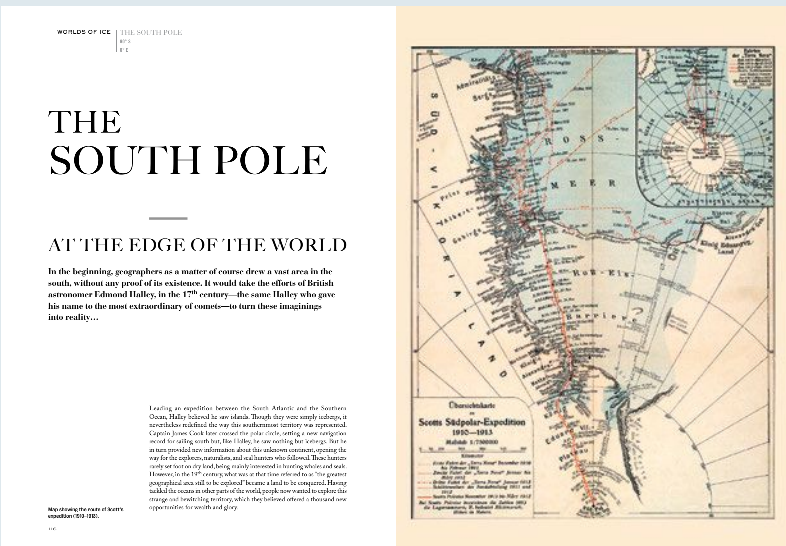
Right:
Map of the kingdom of Siam published in *Le Petit Journal*, 1893.

Pages 20 and 21:
Map of Angkor published by the Indochina Geographical Service in 1932.

18







WORLDS OF ICE | THE SOUTH POLE

THE SOUTH POLE

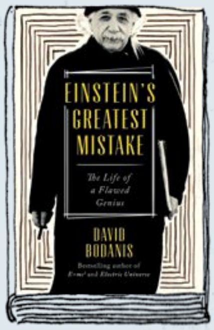
AT THE EDGE OF THE WORLD

**In the beginning, geographers as a matter of course drew a vast area in the south, without any proof of its existence. It would take the efforts of British astronomer Edmond Halley, in the $17^{\text{th}}$ century—the same Halley who gave his name to the most extraordinary of comets—to turn these imaginings into reality…**

Leading an expedition between the South Atlantic and the Southern Ocean, Halley believed he saw islands. Though they were simply icebergs, it nevertheless redefined the way this southernmost territory was represented. Captain James Cook later crossed the polar circle, setting a new navigation record for sailing south but, like Halley, he saw nothing but icebergs. But he in turn provided new information about this unknown continent, opening the way for the explorers, naturalists, and seal hunters who followed. These hunters rarely set foot on dry land, being mainly interested in hunting whales and seals. However, in the $19^{\text{th}}$ century, what was at that time referred to as "the greatest geographical area still to be explored" became a land to be conquered. Having tackled the oceans in other parts of the world, people now wanted to explore this strange and bewitching territory, which they believed offered a thousand new opportunities for wealth and glory.

Map showing the route of Scott's expedition (1910–1913).

116



NON-FICTION

Einstein's Greatest Mistake: The Life of a Flawed Genius
By DAVID BODANIS

*Little, Brown (2016)*
*RRP $35.00*

WE ALL MAKE MISTAKES, for sure, but fallibility is not the first thing that comes to mind when thinking about the most recognisable genius the world has ever produced. David Bodanis, that talented explainer of complex physics to lay readers, whose *E=mc²: A Biography of the World's Most Famous Equation* is among the clearest explanations of the famous formula, has come up with a perfect sequel.

Described by the author as "the story of a fallible genius, but also the story of his mistakes", the book tries to explain the anticlimactic later years of the great man's life. Tourists may have still gawped as Einstein trudged home in Princeton, but during those final decades he was largely ignored by working scientists.

The explanation lies, Bodanis argues, in the same characteristics of imagination and self-confidence that led the young Einstein to change the way we thought about physics forever. As he says, "genius and hubris, triumph and failure, can be inextricable". To understand where Einstein went wrong, it is necessary to examine his earliest years to understand how his mind engaged with the mysteries of the universe.

It began with Einstein's discovery that mass and energy are different forms of the same stuff, expressed in the neat little formula $E=mc^2$ – unheard of at the time, but so dramatically demonstrated as true in the skies over Hiroshima, where a tiny sliver of matter became a knockout blow of energy.

Later came the theory of general relativity that proved energy and mass distort spacetime. The discovery unified gravity into a single view of the universe, no longer a separate force but the result of existing laws. Laws, Einstein thought, that were very clear and very exact. No wonder he considered the theory "the greatest satisfaction of my life".

Ironically though, it was this faith in the perfection of his theory – one could say a blind faith – that closed his mind to other emerging schools of thought, particularly those developing in theories of quantum mechanics. That the quantum world of subatomic particles was a place of inherent uncertainty and contradiction was anathema to Einstein's belief in the underlying laws that guided his own theory. God, he said, "is not playing at dice". And that, to Bodanis, was his greatest mistake. It was also a blindness that kept Einstein in the wilderness for the last 25 years of his life.

With the centenary of Einstein's general theory of relativity last year, there is no shortage of books about Einstein. But this one is still a welcome addition to the vast library. It comes, as mentioned, with Bodanis' talent for explaining the maths and science of Einstein's work. But the best part is the real feel it gives of Einstein the man, and his thinking.

The poor, somewhat arrogant, student of his youth – whose teachers thought would amount to little thanks to his reluctance to take instruction – against the odds gives birth to the in-his-prime scientist combining wonderful imagination and rigour to shake our understanding of the world to its foundations. But that, in turn, leads to a dogmatism that locks him out of a world of new thought that, had he approached the problem differently, he might have contributed so much to.

It's a wonderful exposition of the life of Einstein – the man with the superhuman mind who was, in the end, all too human.

— BILL CONDIE

TOP 5

# Bestsellers

1

When Breath Becomes Air
by PAUL KALANITHI

*Bodley Head (2016)*
*RRP $32.99*

2

The Hidden Life of Trees: What They Feel, How They Communicate – Discoveries From a Secret World
by PETER WOHLLEBEN

*Black Inc. (2016)*
*RRP $29.99*

3

Sapiens: A Brief History of Humankind
by YUVAL NOAH HARARI

*Vintage (2015)*
*RRP $24.99*

4

Being Mortal: Illness, Medicine and What Matters in the End
by ATUL GAWANDE

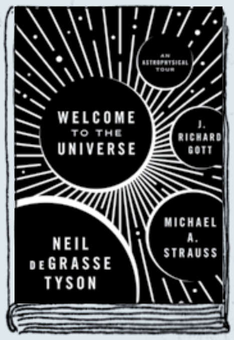
*Profile Books (2015)*
*RRP $22.99*

5

Hidden Figures: The Untold Story of the African American Women Who Helped Win the Space Race
by MARGOT LEE SHETTERLY

*Haper Collins (2016)*
*RRP $44.99*

— FROM THE NEW YORK TIMES SCIENCE BESTSELLER LIST




NON-FICTION
Welcome to the Universe: An Astrophysical Tour
by NEIL DEGRASSE TYSON, MICHAEL A. STRAUSS & J. RICHARD GOTT

*Princeton (2016)*
*RRP $39.95*

THANKS TO *Cosmos: A Spacetime Odyssey*, the 2014 television show inspired by the 1980 Carl Sagan classic, Neil deGrasse Tyson is probably the best-known of the trio of leading astrophysicists presenting this book. But all three share a passion for their subject as well as a long history of helping non-scientific audiences understand the wonders of the universe.

Apart from his television career, Tyson is director of the Hayden Planetarium at the American Museum of Natural History in New York, while Strauss and Gott are professors of astrophysics at Princeton University. Billed as a "personal guided tour of the cosmos", this book is both a wonderful starter pack on astrophysics for newcomers, as well as a charming excursion for the more knowledgeable.

In fact, it is something of a reprise for Tyson, Strauss and Gott, who once co-taught the introductory astronomy course for non-science majors at Princeton (and what a treat that must have been). That series attracted so many students it had to be moved to the biggest lecture hall on campus.

The division of labour in that course saw Tyson teaching "Stars and Planets", Strauss covering "Galaxies and Quasars" and Gott (the author of the wonderfully baffling *Time Travel in Einstein's Universe*) taking on the challenging "Einstein, Relativity and Cosmology" segment. And the book keeps those specialties in place as it moves through three parts, each with its individual author lending his own style to proceedings. (They're all good, but Tyson, with his more practised hand at public outreach, might just have the populist edge.)

The tour they take us on is a comprehensive one, not just unlocking the mysteries of the universe but celebrating the human journey through the years as mankind has grappled with the concepts involved in the cosmos, from Newton to Einstein and Stephen Hawking.

Gott, in particular, is eager for us to see not just the majesty of creation, but the stunning human achievement that has led us to understand as much about the cosmos as we do today.

We should be proud to be members of the human race that in such a short time has learned how gravity works, how stars evolve and just how old the universe is. As he writes: "We are not very powerful, and we have not been around for very long. But we are intelligent creatures and we have learned a lot about the universe and the laws that govern it... It is a stunning accomplishment."

Tyson, Gott and Strauss are each careful at painting a picture of the head-swimming concepts involved, whether that is the basic matter of trying to get our heads around the sheer scale of the universe ("This leaves many people thrilled, but feeling tiny and insignificant at the same time") to finding a contextual point to imagine the density of the neutron star (100 million elephants in a thimble, they say).

Since the three scientists taught the Princeton course, our knowledge of the universe has exploded. Tyson's once-controversial views of the nature of Pluto have been justified, thousands of new planets have been discovered in distant solar systems with the intriguing possibilities that some may harbour life and the Higgs boson and gravitational waves have moved from theory to fact, with the exciting detection by the Laser Interferometer Gravitational-wave Observatory.

The tour takes in all this along with close encounters with quasars and black holes, an explanation of the Big Bang and an introduction to the leading edge of modern theoretical physics – multiverses, superstrings and M-theory. Our guides also introduce the more speculative, in wormholes and time travel, and explain how scientists have, thanks to observations by the Hubble Space Telescope and the Sloan Digital Sky Survey among other tools, developed the standard cosmological model to unprecedented accuracy. They marvel that we have measured the quantity and density of dark matter in the universe without ever having even seen it!

While you don't need to know any science to take the tour, there is plenty here for those who do, with the entertaining narrative bringing new insights to the landscape of the universe and how it formed.

Nor does it talk down to the reader or shy away from some of the trickier and more sophisticated concepts about how the universe works. That said, the mathematics, when it is required, is well and clearly explained and adds to the enjoyment of this weighty volume.

Asked the one thing he wishes more people understood about the universe, Tyson nominates "the incomprehensible depths of time and the mind-stretching depths of space", which "conspire to leave the human mind all but incapable of grasping the entire universe in one thought".

*Welcome to the Universe* is more than a breathtaking guide to the cosmos. It is a unique bridge between popular science and textbooks, admirably achieving Tyson's goal to "empower you to understand the operations of nature".

— BILL CONDIE

# Black lives that mattered to NASA

BOOK
Hidden Figures
BY MARGOT LEE SHETTERLY

*HarperCollins (2016)*
*RRP S44.99*

FILM
*Twentieth Century Fox (2016)*
*In cinemas January 2017*

WHAT A PLEASURE it is to come across an unknown story and for that story to be both true and uplifting. But it is also shocking that the history behind *Hidden Figures* has never been told before.

In 1953, Katherine Johnson, a mathematician who was the first African American woman to attend the graduate school at West Virginia University, was offered a job at the National Advisory Committee for Aeronautics – the agency that was to become NASA. Her job was as a computer – in those days a person, not a machine – calculating the flight paths for space flights, including that of Alan Shepard, the first American in space, in 1959; the trajectory for the 1969 Apollo 11 flight to the moon and vital calculations to get the Apollo 13 crew safely home.

But in the 1950s, with Jim Crow firmly in place, segregation was a way of life. Johnson and other bright female African American mathematicians at the agency, including Dorothy Vaughan and Mary Jackson, might have had their eyes on the stars but on Earth they were forced to stay apart from their white co-workers.

Their story has been brilliantly told by Margot Lee Shetterly, drawing on the personal recollections of the "computers", interviews with NASA executives and engineers, as well as correspondence and reporting from the time. A movie, based on the book, is due for release in 2017.

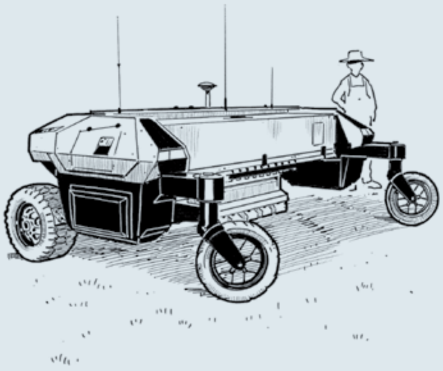
Shetterly, herself African American, grew up in a scientific household. Her father worked at NASA-Langley Research Centre and she knew many of the "hidden figures". "As a child, I grew up knowing so many black people in science, math, and engineering that I thought that was just what black folks did …"

What a pity that insight was denied to the rest of us – until now.

— BILL CONDIE

IMAGE
Hopper Stone. TM & © 2016 Twentieth Century Fox Film Corporation.

GADGET



ROBOT
Agricultural Robot 2
QUEENSLAND UNIVERSITY OF TECHNOLOGY

WEEDS ARE a farmer's biggest enemy and they often requiring toxic herbicides to keep them at bay. But there are problems with this approach, as the longstanding use of the chemicals has bred highly resistant species. As a result, clearing them often requires their physical removal, costing Australian farmers $1.3 billion a year.

That's where the Queensland University of Technology's Agricultural Robot 2, or Agbot II for short, steps in.

Agbot II uses advanced optical and near-infrared sensors to autonomously determine if what it's looking at is a weed or valuable crop. If a weed is detected it can be pulled out or sprayed, reducing the associated cost by up to 90%.

It also means farmers can use fewer herbicides, which benefits not just the crops but the wider environment that can be damaged by herbicide run-off following rain. The Agbot's creators envision future versions that can also feed back data on soil and crop health, even analysing for specific diseases.

Best of all, multiple Agbots can be linked together to form a single team, checking the same spot multiple times to ensure accuracy.

— JAKE PORT

PAUL DAVIES is a theoretical physicist, cosmologist, astrobiologist and best-selling author.

# Abacus

## Make a date with another dimension

**The universe is a lot more complicated than many people think.**

ALICE AND BOB are colleagues at a New York law firm. They are also lovers. They devise a secret tryst at a little-known hotel in Manhattan. "It's on the corner of 58th Street and 12th Avenue," whispers Alice as they stand by the office photocopier. "I'll meet you by the elevators on the 8th floor." Bob smiles and nods.

Alice has specified the location of their meeting by assigning three numbers: 58, 12 and 8. Alternatively, (had the two lovers been geography professors, perhaps) Alice could have used latitude, longitude and altitude. The point is that with three numbers, we can uniquely fix any given point in space, and for that reason we say that space is three-dimensional.

As Bob turns away he realises there's one thing left to settle. "What time, Alice?"

"Tonight, 7pm," she replies.

By adding a fourth number (7, or 19 for those who prefer a 24-hour clock), Bob and Alice's tryst is a planned event in space *and* time, what physicists call spacetime.

Physicists say spacetime has four dimensions. But as with many things in physics, this is not quite as simple as it seems. The three-dimensional nature of space is so obvious and intuitive that most people – even scientists – never stop to think about it. But in 1921 a German mathematician named Theodor Kaluza proposed that our intuition had misled us: he suggested that space really has four dimensions, and therefore spacetime is five-dimensional rather than four-dimensional. He arrived at this bizarre conclusion by discovering an amazing mathematical fact while playing with the period's most important piece of physics: Albert Einstein's general theory of relativity.

Kaluza had taken the equations of Einstein's theory, which were formulated to apply to the familiar four spacetime dimensions, and rewritten them to apply to five dimensions instead. Why? Well, it's the sort of thing mathematicians do. But the result was stunning. Viewed from the normal four-dimensional perspective, Kaluza's equations reduced to those of Einstein's theory, but with an extra set of terms (describing the extra dimension). Surprisingly, these terms corresponded precisely to the description of electromagnetism that James Clerk Maxwell had published decades before (*Cosmos* 66, page 60). By adding an extra dimension of space, Kaluza had, it seemed, accidentally unified gravitation and electromagnetism, two of the fundamental forces of nature.

There was only one snag with this five-dimension theory: where is the extra space dimension? We don't see it. How could we have overlooked something so basic? An answer came a few years later from a Swedish physicist, Oskar Klein. Maybe, thought Klein, we don't notice the fourth dimension of space because it is rolled up to a very small size. To understand what this means, imagine viewing a drinking straw side-on, from a distance. It looks like a one-dimensional line. Only on closer inspection do we see the line is really a tube. Any given point on the 'line' is actually a little circle that's part of the tube. Klein claimed that's where Kaluza's extra dimension was hiding – that what we normally consider to be dimensionless points in space are in reality tiny circles, adding a fourth dimension too small to see or even notice in experiments.

Kaluza and Klein's theory remained

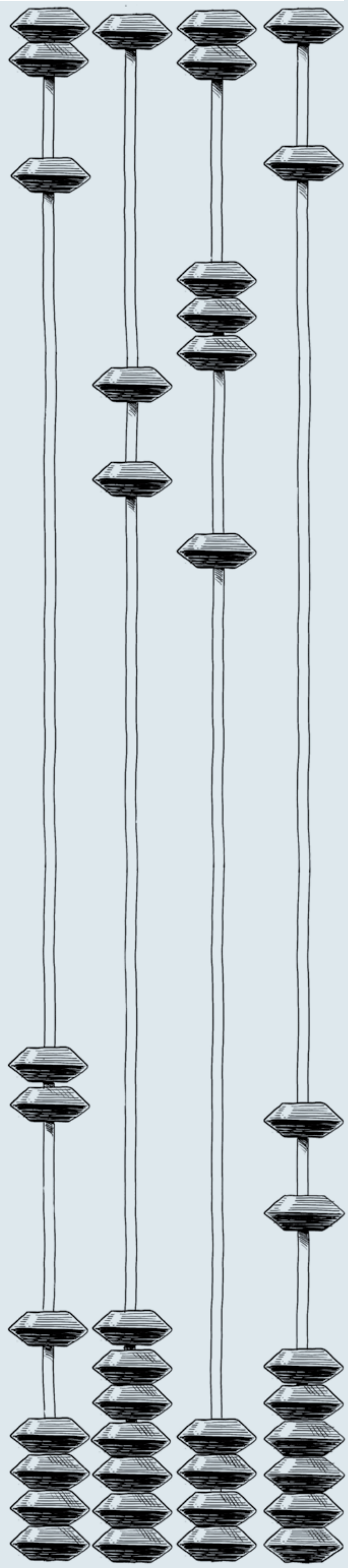
**We may have the dimensions wrong.** ILLUSTRATIONS: JEFFREY PHILLIPS

a mathematical curiosity for some decades, but in the 1970s some physicists began to wonder whether their idea could be extended from just gravity and electromagnetism to include the two additional forces of nature: the weak and strong nuclear forces. Sure enough, it can, although to incorporate these more complicated forces we have to add not just one, but six extra dimensions, making 10 space dimensions – 11 dimensions in total, if you count time.

Just as in Klein's original proposal, the extra dimensions could be rolled up – "compactified" is the technical term – to a tiny size, much smaller than an atomic nucleus. Unlike a single extra dimension, which can only be compactified into a circle, there are now choices: for example, two dimensions can be compactified into either a sphere or a torus (donut shape). For six dimensions, the number of combinations rockets. The particular way the dimensions are compactified affects the properties of the various forces.

The basic idea of unseen extra dimensions has found an enthusiastic reception among string theorists. String theory purports to describe all the forces and particles of nature in terms of little loops of string that wriggle around in higher-dimensional spacetime, with 11 spacetime dimensions a leading contender. String theory is currently the front-runner for a unified theory of fundamental physics.

It took a long while for the idea that spacetime has more than four dimensions to be accepted as a model for real space, but today it is considered the default option. If the idea is right, then compactification is not only critical for physics, but for lovers too. Most of these dimensions are rolled up so small we don't have to worry about them in our everyday lives. So we only have to remember four dimensions, not 11 or more, to keep a rendezvous!

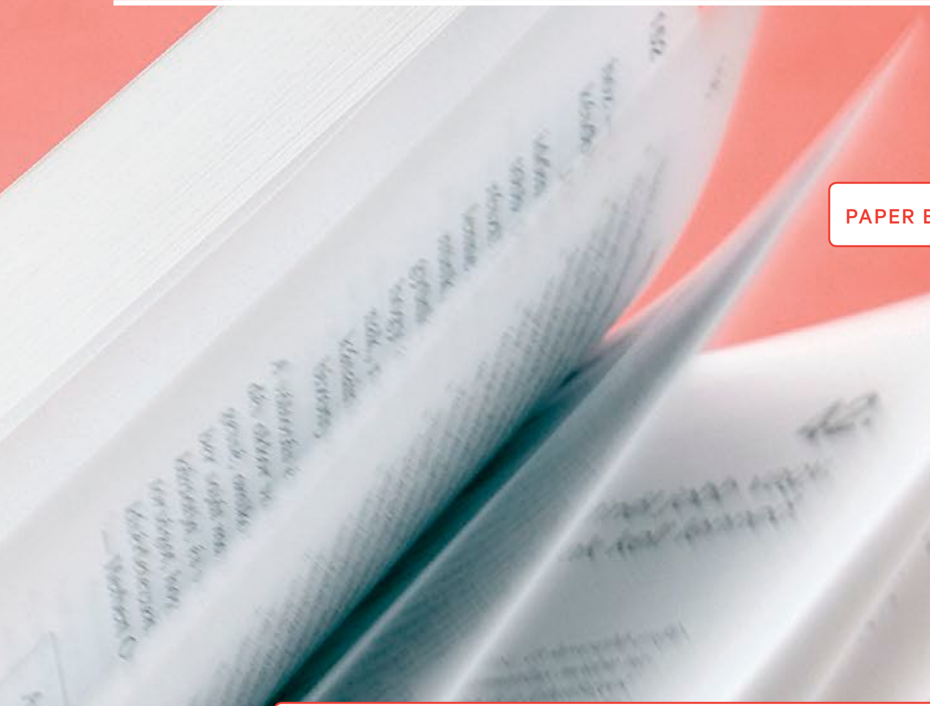


WHY IS IT SO?

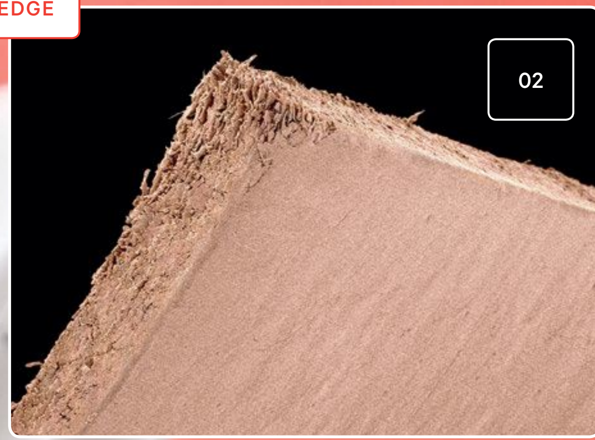
# WHY DO PAPER CUTS HURT SO MUCH?

It's a tiny cut with a very sharp sting. JAKE PORT takes a closer look.

01



PAPER EDGE




IT'S ONE OF THE MOST innocuous of injuries, but also one of the most painful – a paper cut from the filing you've just done or the papers you've neatly ordered. So why do they hurt so much?

Before we explore the answer, it is important to point out that there is very little scientific evidence as to why these tiny lacerations are so incredibly painful. Perhaps pain researchers have bigger questions to concern themselves with than a cut you need a magnifying glass to see.

But taking a closer look at the structure of skin, and the network of nerves and pain receptors that lie within it, does offer a logical explanation.

The topmost layer of skin, known as the epidermis, contains cells that form a protective barrier around your body.

Beneath this is the dermis, where the sweat glands and hair follicles reside, and most importantly, nerve endings also known as nociceptors.

When you receive a normal cut from something sharp, the object will penetrate both these layers, driving into the lower subcutaneous fat layer and onwards into deeper tissue if the cut is very severe. This cut will cause damage to the local nociceptors and expose their sensitive endings to the outside world, triggering a wave of pain (danger) signals.

To make things worse, fingers have a particularly high number of these pain receptors. This is why injuries to your hands tend to hurt a lot more than injuries to other parts of your body, such as back and chest.

When you're cut, blood rushes in, coagulates and seals the wound so the nerves are once again shielded from the outside environment. The initial pain then begins to subside as tissue repair begins under the cover of a newly formed scab.

Paper cuts, though, do not generally penetrate beyond the dermal layer. The fact that only the top layers of the skin are breached means that the blood flow to the area is heavily reduced, preventing a clot and scab from forming and leaving the sensitive nerves exposed.

This is why when you get a paper cut, it's a good idea to tape it shut with a sticking plaster, preferably after applying a dab of antimicrobial ointment. Otherwise, you'll keep feeling a sharp pain whenever the movement of your fingers opens the cut and agitates the exposed pain receptors – not to mention the agonising sting as soap sneaks into the cut the next time you wash your hands.

The level of pain associated with paper cuts is not just down to anatomy, but also the microscopic structure of the paper itself. Looking at the edge of a piece of paper under a microscope (see above) reveals a jagged surface that acts more like a saw than a sharp knife. The serrated edge does not cleanly break the skin's surface and so causes a lot more cellular and tissue damage.

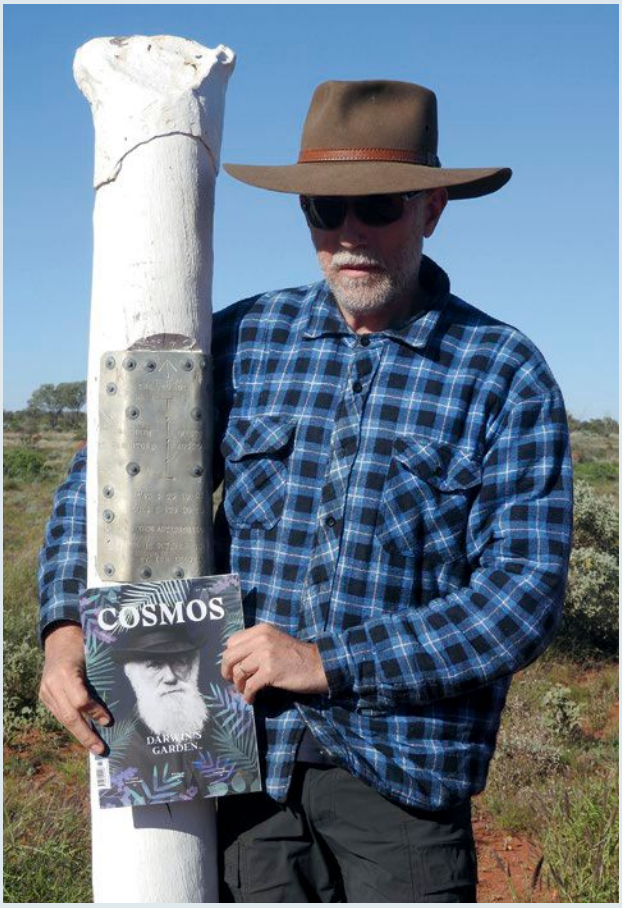
So please be careful when you turn the page.

JAKE PORT, a Melbourne-based writer, contributes to the explainer series on cosmosmagazine.com

IMAGE
01 Jozsef Szasz-Fabian / Getty Images
02 Susumu Nishinaga / Getty Images

ILLUSTRATIONS
Jeffrey Phillips

## WHERE IN THE COSMOS?

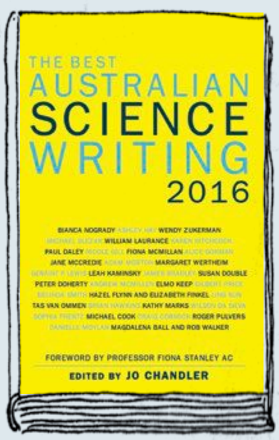



Subscriber Walter Hill was recently at the Western Australia-Northern Territory Border on the Gary Junction Road with his *Cosmos* Magazine.

The markers, one is pictured here, were originally installed by Len Beadell during his 'epic' Gunbarrel Road Construction Party days. Len relied upon astronomical sighting of stars or sun to determine his location; presumably an accurate chronometer too.

## COMPETITION

What year does NASA plan to send another rover to Mars?




Email competitions@cosmosmagazine.com the answer with your name and address by 7 November. Two correct entries will win a copy of *The Best Australian Science Writing 2016*, courtesy of New South Books.

Now in its sixth year, *The Best Australian Science Writing 2016* brings together knowledge and insights from Australia's brightest thinkers as they explore the intricacies of the world around us. This lively collection of essays covers a wide range of subjects and challenges our perceptions of the world and how we exist within it.

## MIND GAMES

# Quiz

Q1. What is the name of the comet that the European Space Agency's Rosetta mission observed?

Q2. After what is the Rosetta mission named?

Q3. Australian Aborigines were found to be most closely related to people from which country?

Q4. How many years ago did the family trees of Australian Aborigines and their closest relatives split?

Q5. Yoshinori Ohsumi won the 2016 Nobel Prize in Physiology or Medicine based on his work on what cellular process?

Q6. Acting as the waste disposal system of the cell, what organelle can break down lipids, peptides, carbohydrates and nucleic acids?

Q7. The Nobel Prize in Physics 2016 was awarded to three physicists born in the UK, but where do they live now?

Q8. What is the name of a molecular compound consisting of a dumbbell shaped molecule threaded through a cyclic molecule?

Q9. What is the name of the protein that forms clumps outside brain cells in Alzhemier's disease?

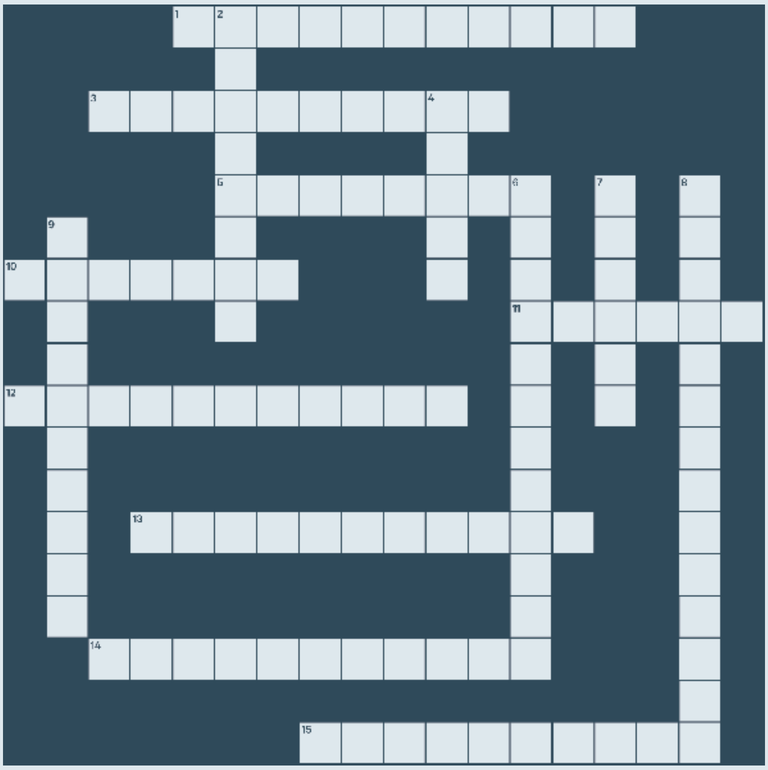
Q10. How many species of giraffe are there?

Q11. What is *Mycosphaerella fijiensis* also known as?

Q12. What is the name of the protein made by tardigrades that protects them from radiation?

Answers will be published in issue 73.

# Cosmos crossword



### ACROSS

1. What is the name of the European Space Agency lander that crashed on Mars in October?
3. Phase _ occurs when matter changes from one phase to another
5. Google's artificial intelligence arm
10. A NASA spacecraft currently exploring Saturn
11. This tissue connects muscles to bones
12. Macromolecule affected by sickle cell disease
13. The order of egg-laying mammals
14. The _ paradox, relating to time travel, is represented in the movie *Back to the Future*
15. Mt Aso, a Japanese volcano, may have stifled what in April?

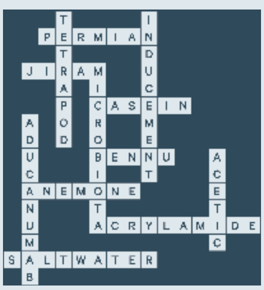
### DOWN

2. Meaning 'dog teeth', the name given to some of the oldest ancestors of modern mammals
4. NASA's manned spacecraft, still in development, intended for Mars and asteroid exploration
6. A chemical used as an early anaesthetic, demonstrated for use in surgery in Boston in 1846 (7,5)
7. Patterns in rings around what planet point to two tiny and as-yet undiscovered moons?
8. The disorder, affecting honey bees, where the majority of worker bees disappear, leaving a queen, a few nurse bees and food (6,8)
9. The geographical region to which naked mole-rats are native (4,6)

Answers will be published in issue 73.

## SOLUTIONS: COSMOS 71

### CROSSWORD



### QUIZ

1. Hydrogen peroxide
2. X Boson
3. They had them wear vibrating sleeves
4. Rod
5. A biofilm
6. Fap2
7. Below sea level
8. Baird's beaked whales
9. They studied how it wobbled
10. Proxima b
11. Lyman Spitzer
12. Destructive interference

## WINNERS

### COMPETITION: COSMOS 71

The type of cancer that causes the most deaths in Australia is lung cancer.

Congratulations to our winners for answering correctly:

Steve Thyer, Lesmurdie, WA;
Janie Carrington, Williamstown, VIC;
Alan Leeds, Rosslea, QLD
and Matthew East, Forster, NSW;
will each receive a DVD copy of *Cancer: The Emperor of All Maladies*, courtesy of Madman Entertainment.

## COMPETITIONS

### WHERE IN THE COSMOS

Send a photo of yourself reading a copy of *Cosmos* Magazine in an interesting place anywhere in the universe to competitions@cosmosmagazine.com.

Tell us your name, the names of others in your picture, your address, what you're doing and why you're there. If published you will receive a *Cosmos* prize pack.

PORTRAIT

# Enrico Della Gaspera, materials scientist


LIKE A CHEF in a kitchen, Enrico Della Gaspera concocts new and interesting creations – but instead of wielding herbs and spices, he works with nanomaterials.

The Italian materials scientist, currently at RMIT University in Melbourne, synthesises minuscule particles called nanocrystals. By deftly combining different sets of ingredients, he can tailor the nanocrystals – metal oxides are one Della Gaspera speciality – for different applications, from medicine to solar energy.

To turn a nanocrystal soup into a useful device, Della Gaspera concentrates the concoction until it can be printed onto different materials, like an ink.

"They'll be cheap and easy to print on any number of surfaces," Della Gaspera says. "Imagine printing layers on glass to make a window which can also produce solar power."

Nanomaterials to his name so far include components of sensors that change colour at the first whiff of toxic gas, thin-film solar cells and coatings that could replace the rare, expensive materials used in electronic devices such as smartphones.

When he's not in the lab, Della Gaspera enjoys experimenting in the kitchen – unless he's cooking for guests. "Then I definitely follow the recipe," he laughs.

— BELINDA SMITH

IMAGE
Peter Tarasiuk