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March–April 2025

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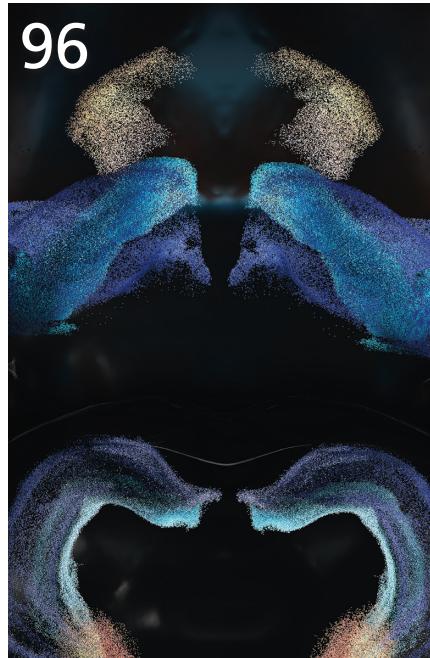
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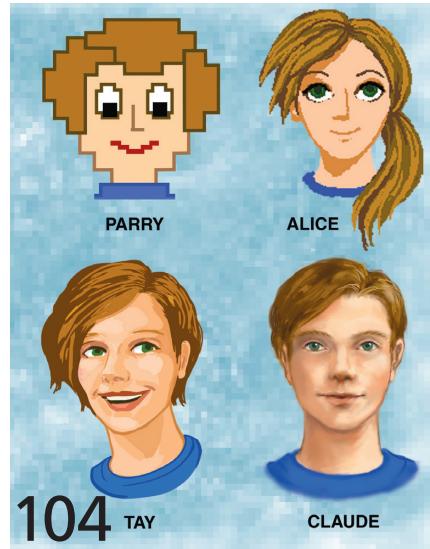
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Federico Fede and Viviana Masia

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The James Webb Space Telescope offers exciting glimpses of our cosmic history.

Caroline Harper

THE COVER



The hippocampus is crucial to memory, which is essential to consciousness. This artist's depiction focuses on a portion of the seahorse-shaped organ. Though not anatomically accurate, it hints at real forms, such as the dentate gyrus (lower left), an adaptive neural circuit vital to learning, memory, and emotional regulation. A thready, high-speed axon network links the circuit to the CA3 layer, a subunit packed with neural connections. CA3 aids in encoding episodic memories and spatial information, and helps us reconstruct memories from partial cues. In "Consciousness: The Road to Reductionism" (pages 96–103), Alan J. McComas gives a historical tour of the key brain areas behind consciousness. He also explains that this organic machine often decides to act, remember, and direct our attention before we are consciously aware of those choices. (Cover art by Greg Dunn.)

Understanding Consciousness

Thinking about thinking is a common human pastime. Our sense of identity seems to drive our consciousness, but it can also make it feel like there's a separate voice in our heads providing running commentary all day long, explains Alan J. McComas. In "Consciousness: The Road to Reductionism" (pages 96–103), McComas describes how decades of neuroscience research have explored the emergence of how humans think and feel, and how conclusions about that process have morphed over time.

McComas argues for a reductionist approach, meaning that consciousness is a function of the brain, and can be explained by analyzing its parts. Interestingly, studies have repeatedly challenged our perception that we are in charge of our consciousness. Neural activity can precede our awareness of tasks that we seemingly decide to undertake, and memory can be activated before our realization of thoughts and ideas. McComas emphasizes that significant questions remain about how our brains create our subjective experiences, but new discoveries are helping us to understand ourselves.

The question of consciousness frequently comes up when people interact with one of the many chatbots now widely available. Devices ranging from smartphone digital assistants, such as Siri, to more recent bots such as ChatGPT, Gemini, and Claude, can seem like they are capable of intelligent responses, and perhaps some level of understanding. The artificial intelligence programming behind these devices is built on massive computing power and algorithmic sophistication that has been developed specifically to mimic human communications, so it's no wonder that these devices can be convincing. But as Federico Fede and Viviana Masia describe in "The Manipulative Side of Chatbots and AI"



Caught in the Moment Photography

(pages 104–111), these programs are also acquiring techniques to use tone and rhetoric that can imitate deceptive and manipulative speech.

Fede and Masia study the restrictions and potential uses of large language models, or LLMs, the technology that allows chatbots to understand and produce natural language. LLMs recognize human patterns of language based on huge quantities of text. This analysis allows the devices to develop parameters that optimize their responses to different types of input. They can identify the broader contexts of sentences, and consider not just the words used, but also phrases, relationships, and boundaries between terms. As most people know, these abilities are far from perfect; chatbots still frequently give wrong answers and, what's worse, will sometimes fabricate information.

Fede and Masia describe how awareness of the rules of rhetoric can aid users in remaining vigilant for when chatbots use manipulative language as they attempt to give more realistic responses. A chatbot may use *implicit communication, presupposition, vagueness, or figurative language* to color their responses. Implicit communication transmits information without it being stated and presupposition represents information that is taken for granted. Keeping an eye open for such usages can prevent users from putting too much stock in chatbot responses that employ them.

In prior issues of *American Scientist*, other authors have discussed how artificial intelligence has infiltrated research, either in data analysis, in generating figures, or even in preparing text. One author wondered when AIs would have to be listed as coauthors. Many journals have issued standards covering the use of AI in submitted papers. But these standards are evolving quickly, and scientists will need to keep pace. —Fenella Saunders (@fsaundersamsi.bsky.social)

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Interpreting Genetics

To the Editors:

In the article "People Are Not Peas" (Perspective, January–February), author Elaine Guevara discussed Richard Lewontin's work on human diversity. Lewontin's flawed interpretation of sparse genetic data has been highlighted in numerous publications. In one refutation, University of Cambridge Emeritus Professor of Biometry A. W. F. Edwards concluded his 2003 article in *BioEssays* with a sentence as prescient as it is humane: "But it is a dangerous mistake to premise the moral equality of human beings on biological similarity because dissimilarity, once revealed, then becomes an argument for moral inequality."

All humans exhibit empathy, inner dialogue, a sense of reciprocity, dread interwoven with hope, and on and on. Thus, we are bound by an ethic of equality. Where, one might ask, would Dr. Guevara draw the line on the number of genetic differences that would invalidate such equality? And what of the 15 percent of differentiating variants that Lewontin found? Are these differences enough to serve as grounds for discrimination?

That these researchers come to such varying conclusions shows genetics, as a subject, can be extremely challenging. High school students already have thousands of important things to learn. If racism is a concern—and it should be—then the ethic of equality, informed by a multicultural emphasis, is a more accessible and efficient lesson.

Justin Vaughn
Athens, GA

Dr. Guevara responds:

Dr. Vaughn raises several thoughtful points that warrant addressing. Edwards argued that although Lewontin's analysis was methodologically sound, his conclusion about race was a "fallacy" because individuals can still be clustered using minor allele frequency differences. Indeed, statistical methods such as those used in the genetics software Structure can assign individuals regional classifications using sufficiently numerous genetic polymorphisms, at least when geographic sampling is discontinuous.

But most human population geneticists do not view Structure analyses as validating racial classification. As biologist Rasmus Nielsen at the Uni-

versity of California, Berkeley, noted in a 2021 book chapter: "The discrete categories used in these inferences are an assumption of the model and not an inference from the data. In reality, human genetic variation is not easily apportioned into discrete categories." Besides, these models typically deviate from traditional continental racial classifications.

D. J. Witherspoon and colleagues in a 2007 article in *Genetics* addressed in detail questions such as "How can the observations of accurate classifiability be reconciled with high between-population similarities among individuals?"—as have other researchers. Regardless, I agree with Dr. Vaughn that genetics can be extremely challenging and that instilling an ethic of equality in students is also meritorious. Genetics concepts nevertheless appear to greatly influence people's views, which underscores the need to bring teaching more in line with modern understandings of genetic variation and the complexity of the relationship between genotype and most phenotypes. Plus, genetics literacy is not only valuable in combating racism, as biologist and educator Brian Donovan and others have demonstrated. It is neces-

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Uncovering Genetic History Across African American Burial Sites

Genetic anthropologist Carter Clinton of North Carolina State University explores the genetic history of African American communities by studying remains from historical burial sites, starting with the African Burial Ground in New York City and later expanding to others. Using minimally invasive methods, he and his team extract DNA from teeth and soil to better understand the genetic identity and health patterns of African Americans over the centuries.

www.amsci.org/node/5335

Exercise, the Gut Microbiome, and Controlling Blood Pressure

Marc D. Cook, associate professor of kinesiology at North Carolina A&T State University, discusses research on how the gut microbiome

mediates blood pressure, as well as evidence on how exercise works through the gut to support reductions in blood pressure and improved cardiovascular health.

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Engineering Bacteria to Eat Plastics

Chemical engineer Nathan Crook of North Carolina State University details research on biocatalysts developed from the bacterium *Vibrio natriegens* to degrade the common plastic polyethylene terephthalate (PET) in seawater, and how the bacterium uses the depolymerization products to provide itself with energy.

www.amsci.org/node/5332

Revealing the Secrets of Huntington's Disease Progression

Biostatistician Tanya Garcia at the University of North Carolina at

Chapel Hill discusses new statistical methods to handle missing data and gain insights into the progression of neurodegenerative diseases such as Huntington's disease.

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sary to prepare students for 21st century life. For example, genetic literacy equips them to make sense of complicated genetic associations with health.

Hi-Fi Preferences

To the Editors:

I read "The Science of Hi-Fi Audio" by John Beerends and Richard Van Everdingen (January–February). I'm a big fan of immersive audio; however, based on the article it appears that the authors and I have very different experiences with it.

What information or sources did the authors use to come to their conclusions? My own experience and knowledge in this area suggests different conclusions.

We should separate the recording, mixing, and producing part of audio creation from the consumer playback part of this conversation. It seems overly intertwined in the article. For example, 99 percent of recording and mixing engineers I talk to say the goal is never to recreate a live event exactly how it sounded because people don't actually like those recordings. The final product is always vastly different from how it sounded, by design. I'd say less than 1 percent of all re-

cordings are meant to capture the live event as it existed.

It's a fool's errand for a consumer seeking high-fidelity playback to expect the immersion of a live event if what's on the recording isn't meant to deliver such an experience. The goal of high-fidelity in my experience has always been to reproduce what's on the recording transparently. High fidelity to the source material (CD, download, stream, etc.) is all that consumers can expect, given that they have no idea what the engineers and producers had in mind when creating the recording. Consumers have to assume what's on the recording is how it's supposed to sound.

Chris Connaker
Minneapolis, MN

Dr. Beerends responds:

As explained in the article, we all have personal experiences and only some of them generalize to shared experiences. However, I agree that the statement "The goal of high-fidelity audio is to capture the feeling of a live musical event" is too strong; it slipped through in the editing process (sorry for that). The essence of the article is that the only shared accepted hi-fi goal is indeed to reproduce what's on the

recording transparently, which comes in two flavors, "here and now" and "there and then," when dealing with the natural reproduction of live recordings. The statement should therefore more accurately be: "One of the goals of high-fidelity audio is to capture the feeling of a live musical event."

The statement "For recording live music, we strive to capture an immersive feeling similar to the experience of the original event" is a personal opinion, but it is backed up my studies, many of which were cited in my original draft text (available on my website, beesikk.nl/JohnBeerends.htm).

A final remark for all hi-fi fans: The proof of the pudding is in the eating, so please try the proposed setup in your own home environment. I would love to hear about your results (johnbeerends@hotmail.com).

How to Write to *American Scientist*

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Mosquitoes' Hothouse Potential

A warmer climate may not limit the habitat range of these disease vectors.

Lisa Couper and her team have gotten very good at seeking out trees with broken branches, because the scars left behind create rain-filled holes that harbor mosquito larvae. Couper, a postdoctoral researcher in environmental health science at the University of California, Berkeley, and her colleagues have been collecting mosquitoes from these tree wells across California and Oregon. Their goal has been to determine whether mosquitoes can rise to the challenge of climate change. And their results so far show that mosquitoes can survive hotter conditions, allowing them—and the diseases they spread—to expand their territories beyond what experts previously thought possible.

"There's a lot of effort and interest right now in projecting how mosquito-borne diseases will shift with changing temperature," Couper says, "and virtually none of those projections incorporate the potential that mosquitoes will adapt to warming."

According to the World Health Organization, mosquito-borne illnesses collectively cause nearly one million deaths each year worldwide. But their distribution is limited primarily by the temperature ranges that mosquitoes can tolerate. All current models of the spread of mosquito-borne disease assume that, with climate change, the diseases will expand into some areas—but withdraw from others that begin to exceed the existing thermal limits of mosquitoes. However, Couper and her team have demonstrated that mosquitoes have the potential to adapt to a warmer world, allowing them to expand their ranges with none of the withdrawal.

To tease out the adaptive potential of mosquitoes, Couper and her team needed to isolate a single population and then subject them to different kinds of heat. The researchers chose to avoid working with the most infamous species of disease-carrying mosquito,

Aedes aegypti, because it would have been a logistical nightmare to ensure they were contained and controlled. According to Couper, "They're invasive, they're not a native species here, and they're human disease vectors." So that's why Couper and her colleagues were poking around tree wells for months, to shop local for their mosquitoes. They settled on a native species, the Western tree hole mosquito (*Aedes sierrensis*), for the artificial heat selection experiments.

How do researchers keep and feed so many bloodthirsty mouths? The team planned to use chicken blood to feed their mosquitoes, but the insects wouldn't cooperate at first. Couper had to sacrifice blood, sweat, and

All current models of mosquito-borne disease assume that, with climate change, diseases will withdraw from areas that begin to exceed the existing thermal limits of mosquitoes.

tears to keep her mosquitoes alive—literally. "I was feeding hundreds to thousands of mosquitoes on my own arm, because I initially couldn't get them to feed on the chicken blood. Thankfully, we got that to work out eventually, but that was probably the lowest point of this experiment." After months in the field gathering the little bloodsuckers, the team could move on.

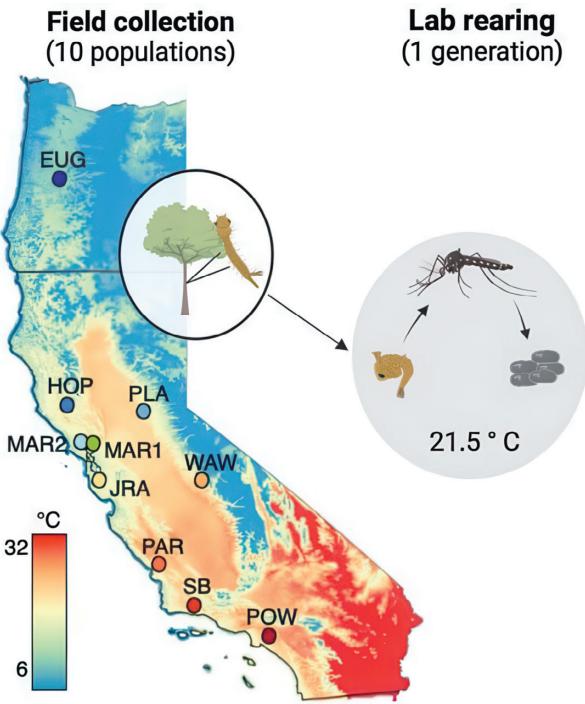
Once they had established a laboratory population of these mosquitoes, the team's first step was to test and

measure their mosquitoes' heat tolerance. The initial starting population of mosquito larvae was split into two groups: one raised at a high temperature of 30 degrees Celsius to simulate the upper thermal limit of mosquito larva survival, and one raised at a control temperature of 20 degrees to simulate the hottest it gets for this species of larval mosquitoes in their natural habitat.

When the surviving mosquitoes from both temperature conditions hatched, the team then measured the heat tolerance of the new adults. The researchers stuck the mosquitoes in individual glass vials, dunked them in a warm water bath, and then recorded how long it took for each mosquito to lose motor functioning. This artificial form of natural selection using heat stress yielded unexpected results.

"We were trying to impose selection such that we're selecting for higher heat tolerance, but what actually ended up happening was that the heat-selected group was less heat tolerant at the next life stage, which was super surprising to us initially," Couper says. "I think that implies that there's some interesting trade-offs in how organisms respond to prolonged heat stress and how they respond to short-term temperature extremes, both of which we know are expected components of climate change." In other words, the mosquito larvae that survived the hotter temperatures may have done so by using up more of their own resources, costing them their fitness in adulthood.

Couper and her team took these results one step further, examining the genomes of their heat-stressed survivors to see if variation in their heat tolerance correlated with variation in their DNA sequences. Previous studies of mosquito adaptability had shown that a specific type of DNA variation was worth looking at: *chromosomal inversion*. This form of structural mutation occurs when segments of DNA break off from the double helix and reattach in the reverse orientation. The inverted regions often bring adaptive versions of genes with them. Sure enough, when the researchers examined the correlations, the mosquitoes that survived the hotter conditions were more likely to have those chromosomal inversions.



A research team visited sites across California and Oregon (map, left) that have variations in average maximum annual temperature. At these sites, the researchers sought out trees with broken limbs, which create holes that fill with rainwater and can harbor mosquito larvae. From each of these tree holes, the team collected larvae (right) that they returned to their laboratory and raised for a generation under the



same temperature conditions (inset). The researchers worked with a local species of mosquito, aptly called the Western tree hole mosquito (*Aedes sierrensis*). The lab-reared generation was then divided into groups that were raised under different temperatures, and the adults were tested for their heat tolerance. Subsequent models showed mosquitoes could evolve at a rate that exceeds that of climate warming.

To determine if mosquitoes could increase their heat tolerance in step with climate change, Couper and her team looked at the mosquitoes' genomes in a different light. By plugging their experimental and genomic data into a simple mathematical model, they could estimate the rate of mosquito evolution and see how it compared with the projected rate of climate change. Couper explains: "If the rate of evolution exceeds the rate of climate warming, then the population might be able to persist. If the rate of evolution is lower than the rate of climate warming, then you would expect it to go extinct. Under most values informed by our experiment, the potential rate of evolution for mosquitoes is greater than the potential rate of warming." Outpacing climate change means mosquitoes, and their deadly microbial contraband, will have access to more victims.

"I hope that other researchers will see this study as a wake-up call, that this is a question that we really need to address in other mosquito species, especially the ones that are most implicated in severe disease transmission," says Zachary Popkin-Hall, a postdoctoral researcher in infectious disease epidemiology and ecology at the University of North Carolina at Chapel Hill.

Popkin-Hall was impressed by what the study authors did, as well as by their acknowledgement of what they

"I was feeding hundreds to thousands of mosquitoes on my own arm because initially I couldn't get them to feed on chicken blood. That was probably the lowest point of this experiment."

didn't do. Couper and her team stated several caveats to their findings, including that their model of the rate of evolution had to make some simplifying assumptions that don't reflect the real world, and that higher temperatures would bring additional stressors such as wildfires and drought that mosquitoes are less equipped to handle.

Popkin-Hall grew up in Northern Virginia and vividly remembers the hundreds of dead crows left in the wake of another disease transmitted by mosquitoes, the West Nile virus outbreak of 2000–2001. "The fact that mosquitoes and the pathogens they transmit could have such a huge impact on the health of humans and other animals made a huge impression on me," he said. He and Couper both agree that these results warrant research and attention from scientists and public health officials alike. Couper hopes to help people living in areas that were previously projected to become too hot for mosquito-borne disease transmission to realize the hothouse potential of these insects. "We don't want to underestimate the potential future mosquito-borne disease risk," she says. "In terms of public health, we need to keep on it with vector control, vaccine distribution, and public health messaging, even in those warmer areas of the mosquito distribution." —Jameson Blount

Jameson Blount is a doctoral candidate in computational biology and bioinformatics at Duke University. He is the deputy editor of the *GeneBites* website. Email: jb621@duke.edu

Redefining Normal

Machine learning models can help identify personal blood count ranges to more accurately monitor a patient's health.

If you've ever had a doctor order a blood test for you, chances are they ran a complete blood count, or CBC. One of the most common blood tests in the world, CBC tests are run billions of times each year to diagnose conditions and monitor patients' health.

But despite the test's ubiquity, the way clinicians interpret and use it in the clinic is often less precise than is ideal. Currently, blood test readings are based on one-size-fits-all reference intervals that don't account for individual differences.

I am a mathematician at the University of Washington School of Medicine, and my team studies ways to use computational tools to improve clinical blood testing. To develop better ways to capture individual patient definitions of "normal" lab values, my colleagues at the Higgins Lab at Harvard Medical School and I examined 20 years of blood count tests from tens of thousands of patients.

In our newly published research, we used machine learning to identify healthy blood count ranges for individual patients and to predict their risk of future disease.

Clinical Tests and Blood Counts

People commonly think of clinical tests as purely diagnostic. For example, a test for COVID-19 or for pregnancy comes back as either positive or negative, telling you whether you have a particular condition. However, most tests don't work this way. Instead, they measure a biological trait that your body continuously regulates up and down to stay within certain bounds.

Your complete blood count is also a continuum. The CBC test creates a detailed profile of your blood cells—such as how many red blood cells, platelets, and white blood cells are in your blood. These markers are used every day in nearly all areas of medicine.

For example, hemoglobin is an iron-containing protein that allows your red blood cells to carry oxygen. If your hemoglobin levels are low, it might mean you are iron deficient. Platelets are cells that help form blood clots and stop bleeding. If your platelet count is low, it may mean you have internal bleeding and your body is using platelets to help form blood clots to plug the wound. White blood cells are part of your immune system. If your white blood cell

We could note when someone's result was outside their smaller personal range, potentially indicating an issue, even if the result was within the normal range for the population overall.

count is high, it might mean you have an infection and your body is producing more of these cells to fight it off.

Not-So-Normal Ranges

But these various tests and measures all raise the question: What actually counts as too high or too low on a blood test?

Traditionally, clinicians determine what are called *reference intervals* by measuring a blood test in a range of healthy people. They usually take the middle 95 percent of these healthy values and call that "normal," with anything above or below being deemed too low or too high. These normal ranges are used nearly everywhere in medicine. But reference intervals face

a big challenge: What's normal for you may not be normal for someone else.

Nearly all blood count markers are heritable, meaning your genetics and environment determine much of what the healthy value for each marker is for you. At the population level, for example, a normal platelet count is approximately between 150 billion and 400 billion cells per liter of blood. But your body may want to maintain a platelet count of 200 billion platelets per liter of blood—a value called your *set point*—which means your normal range might only be from 150 billion to 250 billion.

Differences between a patient's true normal range and the population-based reference interval can create problems for doctors, who may be less likely to diagnose a disease if the patient's set point is far from a cutoff. Conversely, they may run unnecessary tests if the set point is too close to a cutoff.

Defining What's Normal for You

Luckily, many patients get blood counts each year as part of routine checkups. Using machine learning models, my team and I were able to estimate blood count set points for more than 50,000 patients based on their histories of visits to the clinic. This process allowed us to study how the body regulates these set points and to test whether we can build better ways of personalizing lab test readings.

Over multiple decades, we found that individual normal ranges were about three times smaller than those measured at the population level. For example, while the "normal" range for the white blood cell count is from 4 billion to 11 billion cells per liter of blood, we found that most people's individual ranges were much narrower, such as from 4.5 billion to 7 billion, or from 7.5 billion to 10 billion. When we used these set points to interpret new test results, they helped improve diagnoses of diseases such as iron deficiency, chronic kidney disease, and hypothyroidism. We could note when someone's result was outside their smaller personal range, potentially indicating an issue, even if the result was within the normal range for the population overall.

The set points themselves were strong indicators for future risk of developing a disease. For example, patients with high



Javier LARREA/Alamy Stock Photo

A hematologic counter at Donostia Hospital in San Sebastián, Spain, measures the contents of patients' blood samples, which health care providers compare to statistical norms. However, each individual has their own "normal" blood count levels, and comparing their results to population averages rather than to their personal ranges can lead doctors to overlook potential health problems.

white blood cell set points were more likely to develop type 2 diabetes in the future. They were also nearly twice as likely to die of any cause compared with similar patients with low white blood cell counts. Other blood count markers were also strong predictors of future disease and mortality risk.

In the future, doctors could potentially use set points to improve disease screening and how they interpret new test results. This avenue is an exciting development for personalized medicine: using your own medical history to define what exactly "healthy" means for you.

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Brody H. Foy is an assistant professor of laboratory medicine and pathology at the University of Washington. His research utilizes large-scale clinical data to generate physiologic insights and improve patient outcomes, with a focus on the hematologic, respiratory, and cardiac systems. This article was originally published on The Conversation (theconversation.com). Email: brodyfoy@uw.edu

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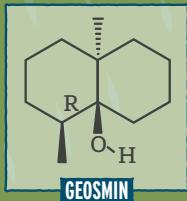
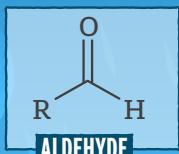
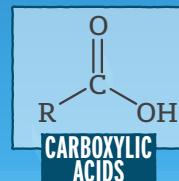
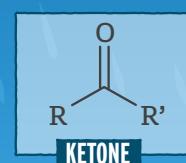
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WHAT'S IN THE SMELL OF FIRST RAIN?

PETRICHOR IS THAT EARTHY SMELL RELEASED BY THE FIRST RAIN AFTER A DRY SPELL.

IN THE 1960S, TWO AUSTRALIAN SCIENTISTS COINED THE TERM FROM THE ANCIENT GREEK WORDS FOR "BLOOD OF STONES." THESE SCIENTISTS, ISABEL JOY BEAR AND RICHARD THOMAS, EXTRACTED A YELLOW OIL – PETRICHOR – FROM DRY ROCKS, CLAY, AND SOIL. IT CONTAINED FATTY ACIDS FROM PLANTS, INCLUDING PALMITIC ACID AND STEARIC ACID. THOUGH THE FATTY ACIDS DON'T SMELL LIKE MUCH ON THEIR OWN, IN SOIL THEY GET BROKEN DOWN INTO SMALLER, SMELLIER MOLECULES SUCH AS ALDEHYDES, KETONES, AND SMALLER CARBOXYLIC ACIDS.



THE SCENT OF FRESHLY TURNED EARTH ALSO HAS A NAME: GEOSMIN.

GEOSMIN IS PRODUCED BY A GROUP OF BACTERIA CALLED ACTINOMYCETES, THOUGH IT'S UNCLEAR WHY. YOU CAN SMELL GEOSMIN AFTER IT RAINS, OR IN YOUR GARDEN AFTER TILLING SOIL OR WATERING PLANTS. OUR NOSES ARE EXTREMELY SENSITIVE TO THIS ODOR: WE CAN DETECT GEOSMIN AT CONCENTRATIONS LESS THAN 10 PARTS PER TRILLION – ABOUT A TEASPOONFUL IN 200 OLYMPIC-SIZED SWIMMING POOLS!

SO HOW DO THESE EARTHY SMELLS REACH OUR NOSES?

DURING LIGHT OR MODERATE RAINFALL, RAINDROPS CAN TRAP TINY AIR BUBBLES BENEATH THEM WHEN THEY HIT THE GROUND OR OTHER POROUS SURFACES. THESE AIR BUBBLES THEN FORCE THEIR WAY TO THE SURFACE, BLASTING OUT IN A SPRAY OF TINY, AEROSOLIZED DROPLETS. SCENT MOLECULES FROM THE EARTH HITCH A RIDE IN THIS AEROSOL AND SPREAD ON THE WIND.

First Principles and Beyond

Chris Pickard is a materials scientist who employs what are called first principles methods—modeling techniques that work out material properties using fundamental rules such as quantum mechanics and Newton's laws. Trained as a condensed matter physicist, he refocused on materials science just as interest in the field was exploding amid advancements in computation. Switching between empirical and theoretical sciences was good preparation for a field that works closely with experimentalists and testers, and that is itself becoming more empirical under the influence of machine learning. Pickard spoke with American Scientist associate editor Nicholas Gerbis about his early successes in studying hydrogen under high pressure, and his hopes for the future of his field. This interview has been edited for length and clarity.

You entered the field in the early 1990s, just as computing power began to enable more complex first principles models. Did you have a sense back then of where things were heading?

The visionaries had an idea of where it would go, but in practice we weren't dealing with very complex or realistic systems. We started, really, with a treatment of the electrons in materials, and we used approximations of equations of quantum mechanics—Schrödinger's equation [a probabilistic description of how quantum particles such as electrons behave] and so on—to describe how the atoms in a material will interact with each other and move around. But the things we're doing now have gone way beyond where we started. It's quite phenomenal, the progress we've made.

Over time, you've been able to reduce constraints, treat atoms less like stacked billiard balls, and cast a wider net for desired characteristics. But where do you begin your search?

I was one of the early people who realized that our computer codes were getting fast enough that we could start to try lots of different possibilities for stacking those atoms together in different patterns. This is what's known as *structure prediction*. I developed an algorithm called *ab initio random structure searching*. You're coming from first principles using quantum mechanics, then you're randomly creating, starting with arrangements of atoms. You feed those into your computer, and you let them lower their energy to a nearby local minimum. If you did that once, you'd probably get a computational mess. But we had access to multicore massive supercomputers where we could do thousands of these

at once. If you try thousands of things at random, one or two of them might turn out to give you something new.

Even with approximations and constraints, is there a limit to how deeply and finely you can drill down into the atomic or quantum world?

If you just have a couple of atoms in a unit cell, which is the repeating unit in a crystal, maybe you don't have to put too many constraints. But as you go to bigger systems, the number of possibilities genuinely grows exponentially quickly. This is what we call the *exponential wall*. It's sitting out there. At some point there's complexity we'll probably never defeat—a large enough collection of atoms. The art in this field is using constraints that can allow you to climb that wall a bit further.

In your early research, the time required to process quantum mechanical calculations limited the questions you could answer. Yet it was during this time that you made one of your most impactful discoveries.

When I started doing postdoc structure prediction work, by chance, my long-term collaborator Richard Needs, another professor in the Cavendish Laboratories at [the University of] Cambridge, came into my office and saw me with all my crystal structures on the computer screen. He asked me, "What's that? What are you doing?" The next day, he met me in the coffee area, and he said, "Can you do what you've been doing with carbon, but for hydrogen?" I said, "Well, that's much easier. There are far fewer electrons." I was very positive. Richard explained that there was this massive problem of understanding the phases of hydro-

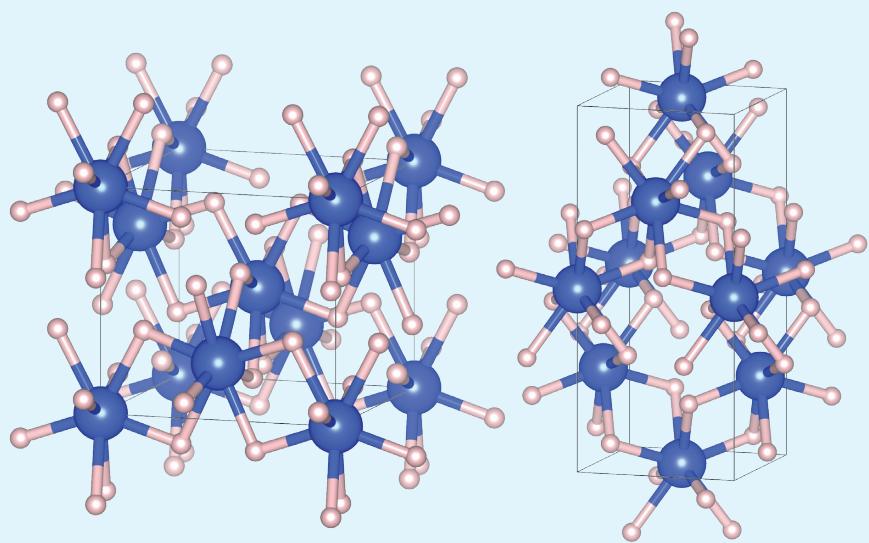


Courtesy of University of Cambridge

gen—which is most of the universe—at high pressure. [In addition to physical phases like solid, liquid, and gas, hydrogen can enter exotic molecular phases under high pressure, exhibiting different crystalline, density, symmetry, and vibrational properties.] The reason is that the protons are extremely difficult to scatter x-rays from; you can hardly see them in a lot of experiments. They can maybe see some spectroscopic signatures, but they had no idea where the atoms were. I started working on that with Richard. And that's why I got into the high-pressure field; without his intervention, I'd have been doing low-pressure materials all along.

That's probably the earliest and biggest hit we had. I published a paper on the phases of hydrogen at high pressure, where we mapped out all the different sequences. We showed that the phase III of hydrogen [a molecular phase, marked by dramatic spectroscopic changes, that occurs at high pressures found naturally in gas giants like Jupiter] matched the spectroscopic signatures. We identified some really curious phases, which were like sandwich layers, a bit like graphene, with hydrogen molecules in between and graphene again. People had never speculated that these phases of hydrogen might exist. And now, all these years later, the results in that paper, plus a few modifications by myself and others, basically define what we know about the structure of hydrogen at these high pressures.

That must have felt like a real validation. When I got those structures, I can remember—I was at that point at the University of St Andrews in Scotland,



Ab initio random structure searching begins by computing random atomic structures and optimizing them using quantum mechanics rules. In their 2011 paper introducing the method, Pickard and colleagues applied it to silane, a hydrogen compound (hydride) of silicon put forward as a possible high-temperature superconductor. The models produced a semiconductor ($I4_1/a$ structure, right) and a slightly less stable $I\bar{4}2d$ structure (left). Though neither was a superconductor, both later proved significant as rare early cases of theoretical structures confirmed experimentally. The search for superconducting hydride structures has taken off recently, accelerated by artificial intelligence and machine learning. Pickard says a balanced approach involving theoretical and experimental methods is growing more essential as scientists seek to push the limits of materials.

my first academic position—the results, they popped off the computer. I remember seeing these new structures coming out, and I'd never seen anything like this before. I just had that feeling. *That's it. That's what we've been looking for.* Of course, you can't carry on working then. I just went for a walk and sat in the sand dunes looking over the beach to digest the consequences of what we'd seen.

Did that open a whole new research area for you?

The early days of doing this structure prediction from first principles were extremely productive. Everything we tried, something new came out. It was like having a new telescope, looking down through the telescope, and seeing all these galaxies and so on. It's not so easy now, because I think we picked off a lot of the simple problems. As time goes on, people ask more detailed questions. But that was a very exciting time, those few years.

Does hydrogen, which is almost on the scale at which quantum rules take over, present special challenges?

Absolutely. It's on the edge. That's what makes it really complex. The

lightness of the proton means that you can't entirely assume that the atom itself is behaving classically. Of course, the electrons are behaving quantum mechanically,

“You don’t have to be a hero and do it only one way or the other. Working together moves things on faster.”

but with hydrogen the quantum mechanics of the proton come into play as well.

Maybe I was overly optimistic or naive when I said to Richard, “Of course, hydrogen’s easy.” But for me, it was easy, because it only had one electron; it was a simple system. But the fact that it’s on the edge of being a quantum particle as well means it’s incredibly rich. Keep studying hydrogen, you keep finding new things.

Has machine learning affected your work and your field’s ability to tackle more complex structures?

There’s been a huge revolution in the last five years. Now, instead of doing all your calculations solving the Schrödinger equation, we calculate the Schrödinger equation for a set of example structures, and then we train a machine learning model or neural network to interpolate between those different configurations. When we calculate the energies of the atoms or move the atoms around, we can use the neural network to guess what the energies might have been from a quantum mechanical simulation. It might be 100,000 times faster. One of the really exciting applications in this area—not by me, but by my colleagues—has been to explore the amorphous state for realistic materials [in which molecules are disordered and noncrystalline]. Model amorphous states have been studied for a very long time, but now, with this machine learning acceleration, we can do it for essentially any chemistry you might think of.

Can you find the first principles within the machine learning results?

You can look at it in different ways. On the one hand, the beauty of doing things from first principles is, somewhat counterintuitively, it’s easy for people who are not experts to use. Because the method is rooted in the solid equations of reality, there aren’t too many parameters for users to fiddle around with. This was always the attraction. When I got into the field in the early '90s, I was part of the group of people who were reacting against empirical models—models based on parameters that people tuned. We were very proud that we were doing things from first principles. There were approximations, but within those approximations we could lock down those calculations. Now, of course, we’ve gone back to empiricism. Machine learning is an empirical approach: It’s statistically fitting functions with uncertainties. You don’t necessarily have to have done everything from first principles; you can adjust things to match with experiments.

I would say that this is something that we’ll start to grapple with. If someone does a quantum mechanical calculation in one lab and then someone else does it in another lab, if they agree on their parameters, they

should get the same answer. But different people have different machine learning models, maybe trained on the same data or maybe on different data. They may not agree. That may be fine, but it means you'll have to try and understand these uncertainties in the models.

I imagine people in fields with such potential to produce world-changing materials must be under considerable pressure. Has that been your experience?

It was something I was challenged on when I was applying for a fellowship based on this structure prediction. "All well and good, Chris, you can predict these crystal structures. But how are you going to make them?" I said, "Okay, I'm producing a map, where I'm telling you where the cities are, but I'm not giving you the roads between them." The task is to have not just computational materials discovery, but computational materials discovery with a set of instructions as to how to make it as well. This is a challenge. In organic chemistry, there are a lot of skills in creating a lot of varieties of molecules. It's more difficult in solid-state chemistry. I'm posi-

tive about the advances in machine learning and so on. Maybe we can do more, explore wider ranges of configurations, temperature conditions, pressure conditions, precursors, to maybe find a computational route to helping with the instructions.

What are the next materials you hope to tackle? What else is your research group working on right now?

There's a range of projects that we're looking at. I've had a long research project working on prediction, discovery, and then also experimental discovery of novel superconductors based on pure hydrogen or materials with high hydrogen content. We're looking at the behavior of metals with maybe some exotic electronic structure effects. Also, we have a project that has been going for a few years where we're using these techniques to try and discover, computationally, new materials for batteries—new cathode materials. Of course, that's a difficult challenge. There are lots of very good materials for batteries already out there, and I wouldn't claim that we're going to make any big change to that.

What are your hopes for the future of your field?

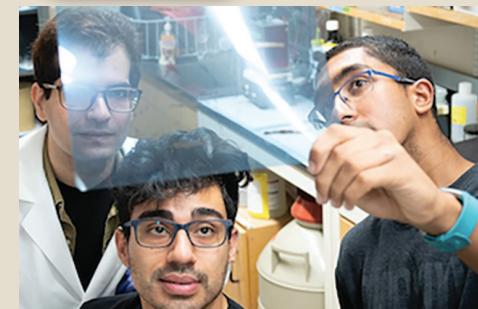
It's kind of a gold rush moment, where everyone can do things that no one's done before. This breakthrough in machine learning is making a lot of things that I thought I would never do in my career suddenly move forward 10 or 20 years. It's interesting that it's happened at the same time as a lot of hype around AI. Of course, there's that public excitement. But for us, it's an optimization or an accelerant to an existing technology.

Even though I came from very much the first principles, ab-initio-or-bust kind of way, as time goes on and you get confronted by more realistic problems, you appreciate that this balanced approach is probably the most productive one. I like to say the ideal situation is to do the right amount of computing and the right amount of experiments to get to the answer that you're looking for as quickly as possible. You don't have to be a hero and do it only one way or the other. Working together moves things on faster. ■



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In this roundup, associate editor Nicholas Gerbis summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi

Waking Antarctic Volcanoes

The loss of surface ice in the West Antarctic Ice Sheet, accelerated by climate change, could cause more volcanic eruptions in the region by speeding ice melting and triggering a melt–eruption feedback loop, according to a team led by researchers at Brown University. The computer simulation data suggest the ice losses could further raise sea levels, perturb



Josh Landis, U.S. Arctic Program, Public Domain

climates, and threaten ecosystems. The ice sheet sits atop one of the world's largest volcanic provinces, which comprises more than 100 potentially active eruption areas both above and beneath the ice. As melt and runoff decrease the ice's compressive weight, the Earth's crust will rebound like a ragged foam mattress, sealing old fractures, opening new ones, and allowing magma to flow into shallower chambers. Declining pressure will also let more of the mantle partially melt (rocks under reduced pressure require less heat to change state) and add gas pressure to magma chambers from released water and carbon dioxide, potentially triggering further, more explosive eruptions over the coming centuries.

Coonin, A. N., C. Huber, J. Troch, M. Townsend, K. Scholz, and B. S. Singer. 2024. Magma chamber response to ice unloading: Applications to volcanism in the West Antarctic Rift System. *Geochemistry, Geophysics, Geosystems* 25:e2024GC011743.

Thinking at 10 Bits per Second

Based on tests involving speed memorization, speech, and the game *StarCraft*, scientists at the California Institute of Technology have clocked the human brain's

processing speed at a measly 10 bits per second. That suggests that neuroprostheses might perform motor functions with less input than once believed, but it also renders brain-to-computer interfaces moot—at least within the study's information theory framework, which depends strongly on how actions, decisions, and "bits" are defined and measured. While it is perhaps mortifying to learn that we perceive, act, and imagine at early telegraph transmission rates, it is also baffling because the peripheral nervous system (which feeds our perceptions and informs our decisions) absorbs environmental data at closer to 6G speeds. The discrepancy between these "inner" and "outer" brains raises other questions, such as why we think and act serially, like a cook following a recipe step-by-step, while our senses process data in parallel, like a kitchen crew handling a full restaurant's meals and prep steps in tandem; how the dribble of human thought can interface with the torrent of sensory flow; and why we evolved to use the same neural architecture for such disparate data rates. The authors note the limits of their measurement methods, but add that humans might have evolved such low-bit-rate thinking simply because it was sufficient or advantageous to survival.

Zheng, J., and M. Meister. 2024. The unbearable slowness of being: Why do we live at 10 bits/s? *Neuron* 113:192–204.

Squirrels that Hunt

In the first clear evidence of squirrels preying on vertebrates, scientists have documented 74 instances of California ground squirrels (*Otospermophilus beecheyi*) hunting, killing, eating, and competing over California voles (*Microtus c. californicus*). Though squirrels generally eat seeds, nuts, and fruits, they are behaviorally flexible and sometimes expand their diets to include insects or even eggs or hatchlings. The authors, led by researchers at University of Wisconsin–Eau Claire, believe the predation was triggered by a 2024 spike



Sonja Wild/UC Davis

in the local vole population. Squirrels are adapted to capitalize on *pulses* (sudden appearances of large amounts of food), though these surpluses typically comprise acorns or tree nuts, not hamster-like mammals. Squirrels are highly social, but the hunters worked alone and, though the scientists saw some social tolerance during feeding, they also noted unusual aggression and dominance displays around the killed voles. It's unclear how kinship or family ties affect such conduct, or whether hunting behaviors, which occur across ages and sexes, arise from social learning or genetic predisposition. Either way, predation could affect population and community interactions and evolutionary fitness, as well as disease dynamics among two reservoir species of the plague-causing bacterium *Yersinia pestis*.

Smith, J. E., et al. 2025. Vole hunting: Novel predatory and carnivorous behavior by California ground squirrels. *Journal of Ethology* 43:3–12.

Dim, Strange Nova

A team led by researchers at the University of Warsaw has found new space objects, dubbed "millinovae," that send out nova-like bursts of low-energy x-rays without ejecting huge masses of matter. Typically, a nova occurs on the surface of a white dwarf (a dense, compact, and burned-out star remnant) that shares a binary system with a main-sequence star or a red giant. Gravity causes matter from the companion star to swirl inward and build up on the dwarf's surface, ultimately triggering an explosion that releases the telltale x-rays and the equivalent of up to one-tenth of the Earth's mass in matter. But ASASSN-16oh, the first millinova found, showed no mass ejection and took months to fully brighten, compared to the hours or days typical of a nova. The lack of matter expelled by millinovae could mean more mass remains to accumulate on the white dwarf's surface; if so, enough could eventually build up to cause a Type Ia supernova. So far, the team has found 28 other millinovae in data from the Optical Gravitational Lensing Experiment (OGLE) survey. They lie in the direction of the Magellanic Clouds, two galaxies that are among the Milky Way's closest neighbors.

Mróz, P., et al. 2024. Millinovae: A new class of transient supersoft x-ray sources without a classical nova eruption. *Astrophysical Journal Letters* 977:L37.

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Self-Organized Scales

The skin on crocodilian faces forms into scaly patterns through mechanics, not genetics.

Ababy Nile crocodile hatches out of its egg, its small body covered with patterned scales. But the scales on its face are irregular, long on top of its snout but smaller and more clustered on the sides of its jaw (*opposite, top*). And the scales aren't the same on the left and right sides of its head, either. Indeed, the pattern is unique to each individual. "They don't have fingerprints, but they have face prints," jokes biophysicist Michel Milinkovitch of the University of Geneva.

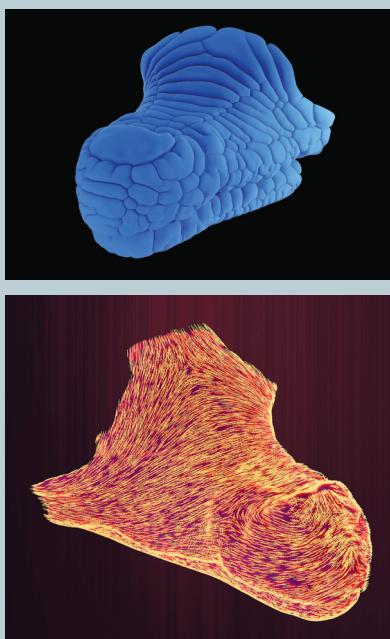
Milinkovitch studies patterning in biological organisms, and he and his team had figured out that this face scale growth is solely a mechanical process, not governed by genetic factors. The scales there are not individual units, but are formed as the skin grows by area borders propagating and connecting. But what growth processes govern this patterning? Milinkovitch and his team wanted to know if the skin is being compressed into folds, or if it is being pulled apart into indentations that are more like cracks that form in a drying mud patch—but in this case brought on by the rapid jaw growth of baby crocodiles.

The researchers developed a 3D laser-imaging technique so they could view the developing scales of the embryonic crocodiles (*opposite page, bottom*). Their data showed the increasing complexity of the skin folds over gestation time, but also revealed that the skin continually gets stiffer during the process. The skin also was growing faster than the underlayer of stiffer tissues to which it was attached.

By injecting the embryos with a protein that promotes growth of only the epidermis, the top layer of the skin, the team was able to see that the process was caused by compression, not tension. If the skin was in tension, faster growth would make it smoother. Instead, the team saw that the protein-treated crocodiles had more skin growth, which formed convoluted, labyrinthine patterns made of smaller, denser scales, as the fast-growing epidermis was constrained by the slower-growing underlayer of skin, or dermis, it was attached to, and therefore buckled and folded.

Milinkovitch explains that similar mechanical processes govern the formation of brain folds, protrusions called *villi* in the intestine, and nose surface patterning in dogs and cows.

To understand the skin structure further, the team developed a dye technique to image the collagen fibers that underlie it (*below, bottom*). These fibers play a major role in how the skin forms, and they resist tension, said Milinkovitch. They found that in crocodiles, the collagen fibers are aligned perpendicularly across the top of the jaw—in keeping with the elongated scale pattern found there—whereas the fibers form a more random, crosshatched arrangement along the sides, where the scales cluster together more closely.

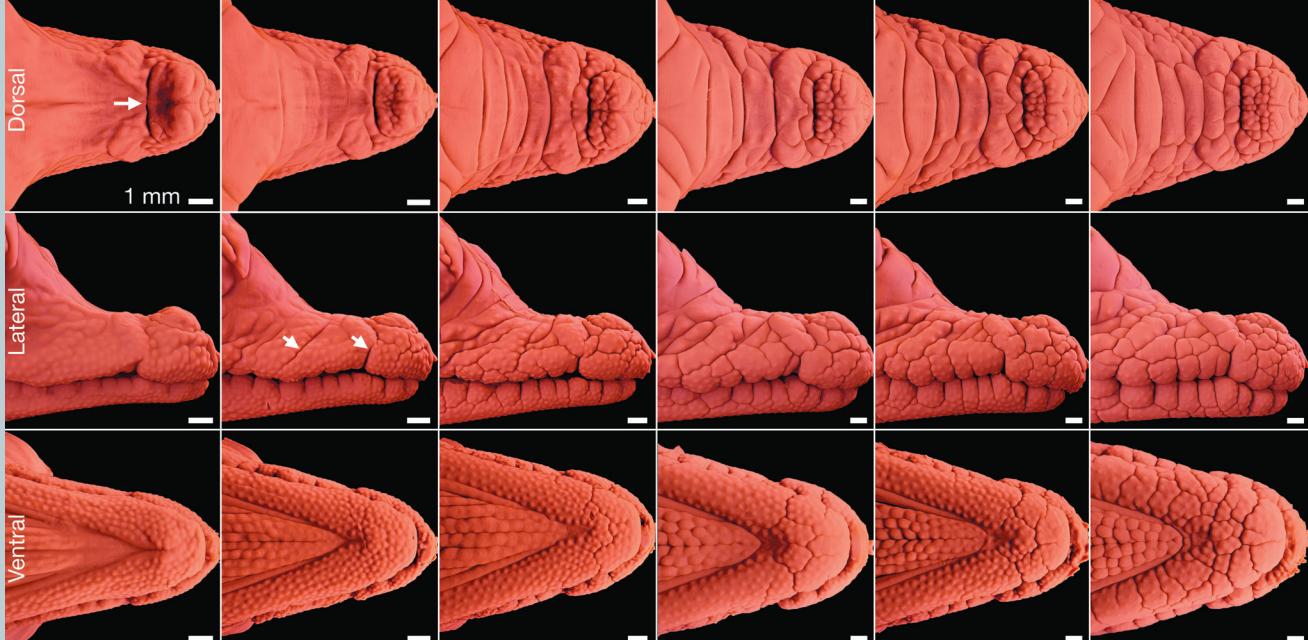


seen on the faces of other crocodilians, such as spectacled caimans or American alligators, again indicating that these were all mechanical and not genetic growth processes.

As a bonus, the model also accurately simulated the bumps on the inside of the crocodile's mouth, which the researchers hadn't explicitly programmed into it. "So for free we got the patterning of the palate," says Milinkovitch. "It emerged from the same process, which was super cool, because it was an independent test of the validity of our model."

Milinkovitch emphasizes that mechanical patterning can be an underappreciated mechanism in biological development. "In multicellular organisms, you start from a very simple cell, and then you develop into something super complicated, and we still don't completely understand how this patterning process works," he says. "There are tons of processes that are at the interface between biology and physics, so it cannot be all genetics, and there is no way we can pretend to understand development if we ignore mechanics." —Fenella Saunders

A crocodile's scales grow differently on its head than on the rest of its body. The scales on the top of its snout are elongated, whereas the ones on the sides are clustered (right, with imaging overlay). The pattern is different for each individual. Researchers have imaged Nile crocodile embryos to show that the property is mechanical, not genetic, and arises as the skin grows faster than the underlying stiff tissues, buckling and folding (bottom). Imaging of the underlying collagen fibers shows support for these emerging structures (opposite, bottom), and modeling (opposite, top) proves the process.



Santos-Durán, Cooper, Timin, Jahanbakhsh, and Milinkovitch/University of Geneva



Bookcases and Bedpans

The ingenuity of Norman Heatley made life-saving penicillin practical.

Ainissa Ramirez

Alexander Fleming was a Scottish bacteriologist who possessed a streak of play. Inside his London laboratory, he mostly thought about mechanisms to stave off illnesses caused by germs. Usually, he smeared straight lines of bacteria onto agar-coated petri dishes during his experiments. But sometimes Fleming painted pictures with them, and even left the dishes out for extended periods. On one September day in 1928, Fleming was busily cleaning petri dishes that he had left before his summer vacation, and he noticed something in one of them. Colonies of staphylococci were succumbing in locations next to a mold that had contaminated the petri dish as it sat during his time away. Curious, Fleming captured part of the mold and grew it in a broth. A white, fluffy mass grew on top of the broth, followed by a dark green felt. A few days later, the broth turned a bright yellow. Fleming identified the mold as a member of the *Penicillium* genus, and he believed that the mold was secreting some antibacterial substance into the broth. He filtered the mold's broth and called it "penicillin."

This bacteriologist then spread penicillin onto a petri dish next to stripes of different menacing bacteria. Fleming witnessed that it inhibited the growth of *Staphylococcus* and *Streptococcus* species, *B. diphtheriae*, as well as *pneumococcus*, *meningococcus*, and *gonococcus*, but not the germs behind cholera, tuberculosis, and dysentery.

His discovery was promising, but to make it useful for humans, he needed gallons of this filtrated mold broth. The task of purifying, strengthening, and mass producing the elixir trapped inside of this liquid was beyond Flem-



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By all accounts, biochemist Norman Heatley was a shy, meek man, but he had a knack for turning discarded parts into essential scientific gadgets.

ing's skill set. So in 1929, he wrote up his findings in hopes that the right scientists would carry on his work.

Unlocking Penicillin

Ernst Chain read Fleming's paper in 1938. Chain was a biochemist who was part of the Oxford University research

team led by Howard Florey, a professor in the Sir William Dunn School of Pathology, which was looking for new antibacterial substances to investigate. In October 1939, a new biochemist joined Florey's team. Norman Heatley was recounted by many to have been a thin, shy, and overly polite young man. Although Heatley seemed meek outside of the laboratory, he was MacGyver inside of one. It was a good thing, too. Just a month before Heatley came on board, Great Britain declared war against Germany, making it more difficult to conduct scientific research as laboratory supplies became limited. Fortunately, Heatley had a knack for making scientific gadgets from broken and discarded parts.

One of Heatley's roles was to take over the cultivation of the mold that Chain had learned about from Fleming's paper, while Chain focused on methods to purify and isolate the antibacterial substance from the filtrated liquid under the mold and learn about its chemical nature. The Oxford team called this specific substance penicillin (although Fleming had called the entire liquid by the same name). Heatley explored every variable to increase the productivity of the mold—from additives to optimal broth height. Additionally, Heatley had to determine how much penicillin was in each batch of filtrated mold broth, with the goal of increasing the concentration. The conventional way to evaluate the effectiveness and potency was

QUICK TAKE

Although Alexander Fleming first identified the penicillin mold as antibacterial, he was not the first to extract, purify, and mass produce the antibiotic that would change modern medicine.

Ernst Chain and Howard Florey of Oxford University carried on the work, but they relied on biochemist Norman Heatley to develop ways to grow and extract the substance.

Heatley's ingenuity eventually led to the large-scale manufacturing of penicillin, but his pivotal role in the process was not recognized and lauded until many years later.



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During the first scaled-up production of penicillin at Oxford University in England, custom-manufactured culture vessels were stacked in racks as densely as possible. Their output was monitored by a group of women who became known as Oxford's "penicillin girls."

to get a sample, dilute it, put it in a petri dish along with bacteria, and then wait. But Heatley found this method to be "an awful bother." Plus, it was difficult to compare how well one batch killed bacteria relative to another.

Heatley cleverly devised a better way. He inserted six small glass cylindrical tubes into the agar, then filled each tube with the different penicillin-containing liquids that needed to be evaluated. The petri dish was then sown with bacteria and incubated. As the liquids from the glass cylinders seeped into the petri dish, they killed the surrounding bacteria, creating a circular zone that made the amount of penicillin in the fluid visually obvious. Heatley would then pass along any promising batches to Chain.

Unlocking the penicillin substance from the filtrated mold broth was one of the challenges the Oxford scientists faced. A few years earlier, in 1932, a team at the London School of Hygiene and Tropical Medicine had investigated a strain of mold from Fleming's lab and

found that, if the penicillin-containing liquid was acidified and then mixed with ether, the penicillin substance would leave that liquid and go into the ether. This step was key in isolating penicillin, and the Oxford team employed it. But here is where Chain got stuck. Now that the penicillin was inside the ether, he couldn't figure out how to get it out.

Heatley suggested using penicillin's testy temperament to their advantage. The literature had shown that penicillin didn't like environments that were too acidic or too alkaline. With this bit of information, Heatley came up with a two-step method to encourage penicillin to move from one liquid to another. To prove this process, he performed a quick experiment. He added acid to the mold broth and poured the mix into a jug along with ether. Then he shook the jug. This mixing allowed the penicillin to move into the ether. With time, these two immiscible liquids separated like oil and water. Heatley then drew off the ether, which contained the

penicillin. His next step was to get the penicillin substance out of the ether. To do so, Heatley added slightly alkaline water to the ether and then shook the bottle. This time, the penicillin went from the ether to the water. The resulting water solution was then freeze-dried, resulting in the generation of a stable and potent brownish powder. Heatley's breakthrough of chemically yo-yoing penicillin—also known as *back-extraction*—would become crucial to the Oxford team's efforts.

Heatley later devised a contraption to semi-automate this process. A library's discarded bookcase held up jugs of the filtered mold juice, a solution of 10 percent phosphoric acid, and an organic solvent (ether, and later, amyl acetate). The filtrated mold broth was cooled through a coil to keep the penicillin stable, and then it was acidified. This liquid was then passed through jet nozzles to make fine uniform droplets that fell into a column of the organic solvent, taking in the penicillin. Using gravity, liquids flowed through an assortment of hoses and specialized funnels with a buzzer to indicate when the bottles were full or empty. Florey thought the



History of Science Museum, University of Oxford

When looking for vessels for growing penicillin, options during wartime were limited, so Heatley tried out insecticide cans (top left) and biscuit tins (bottom left) before settling on bedpans (top right) because they provided better surface area. However, there weren't enough bedpans available, so Heatley ended up designing his own vessel that was manufactured from clay (bottom right).

apparatus was temperamental. But Heatley had created what was then the world's best penicillin extractor, and he proudly pasted a photo of it on the back cover of his personal diary. By March 1940, Heatley and Chain had 100 milligrams of penicillin. This amount was enough to test not just on bacteria, but on eight white mice with infections.

Scaling Up

On the weekend of May 25, 1940, Florey injected half of these mice with penicillin, and Heatley noted how they were doing in his notebook. By Sunday morning, only the four controls were dead, making it "clear cut" to Florey that penicillin had the ability to reverse a bacterial death sentence. To make sure that what they had seen wasn't a fluke, the team repeated the experiment two more times with greater numbers of mice, achieving the same result. With their newfound confidence, the next step was to test penicillin in humans. But according to Florey's calculations, a human was 3,000 times the size of a mouse. As such, they were going to need much more penicillin, and thus much more mold and much more real estate to grow it. Heatley took on this task of creating a fungus factory within the Oxford building.

This resourceful young scientist hunted for the best container to provide the greatest amount of flat area for the mold to grow. At first, he grabbed whatever glassware was available in the lab, such as Erlenmeyer flasks. But soon Heatley began to look for other containers that provided more surface area and that could be stacked. He tried an enamel pie dish. This pan provided more area, but it didn't have a cover. He tried biscuit tins and added a spout, which made it possible to pour in nutrients and later retrieve the penicillin-containing liquid. But soon these tins became hard to obtain during the war. Heatley purchased a rectangular metal can for insecticide, tins for motor oil, and portable gas tanks, too. After exploring many different containers, he eventually found the best option for growing mold was located in the nearby Radcliffe Infirmary—the bedpan.

These enamel bedpans had lots of surface area, a cover, and a spout. Heatley requested 600 of them from the Medical Council, the medical governing arm in England at the time, to start the mass production of penicillin, but that number of pans wasn't available. Florey tried to order a glass version of the bedpan, but during the war there

was a limited supply of glassware for civilian activities. To acquire a suitable container, Heatley had to have it custom-made, using an old material that was abundant in England—clay.

When designing his new penicillin culture vessel to be fashioned from clay, Heatley borrowed the best features from the bedpan that had inspired him. Having a spout was a key element to incorporate, but instead of the container being a circular shape, Heatley wanted his clay version to look more like an oversized book, with the spout on the short end near the corner. This shape allowed multiple vessels to be stacked on top of one another with access to their spouts. Additionally, each clay specimen needed to be glazed only on the inside. The rough outside would provide better friction, preventing containers from sliding because of vibrations from a passing truck or an air raid. Heatley's next challenge was to find a manufacturer for these clay vessels in the midst of the war.

Florey happened to know a physician from Stokes-on-Trent, an English city also known as "The Potteries" and home to many tableware manufacturers. Florey reached out to his colleague, and within a few days he had the name of James Macintyre & Co., Ltd., which could make lots of pieces for them. The Oxford team needed at least 300 vessels. It took the mold about 10 days to create penicillin, and they wanted to harvest from 30 vessels a day. Heatley made a visit to inspect what the firm could make, and Florey authorized the purchase of 600 units. The manufacturer was quickly and steadily making the vessels, but shipping them would take some time. When this news reached Oxford, it propelled Heatley to take a road trip.

Two days before Christmas in 1940, on a cold winter night, Heatley drove about 300 kilometers to fetch his specialized clay vessels. The road from Oxford to Stokes-on-Trent was winding, snow-covered, and unmarked, because street signs had been removed to confuse any invaders. Heatley chauffeured back the first 170 of the clay "bedpans," which were encased in protective straw. Driving a borrowed emergency services van and traveling at slow speeds, Heatley recalled that he winced every time he hit a bump in the road, with thoughts of his fragile cargo. When he finally reached Oxford many hours later, Florey jokingly thanked him for picking up the bedpans.

Clinical Trials and Tribulations

That Christmas Eve, the clay vessels were prepared. First, they were washed to remove any excess silt. Each was then fed with nutrient broth and placed in an autoclave, where the broth was heated under pressure at temperatures that didn't harm its nutrients, but sterilized it and removed living contaminants that would impede the growth of the mold. Once completed, all the containers were set on their flat side with their spout up. They were each seeded with penicillin spores, and the spouts were sealed with cotton plugs to prevent further contamination. In 10 days, the broth would contain the bright yellow liquid that would then be harvested for extraction.

The esteemed operating theater of the Sir William Dunn School of Pathology had become a penicillin pilot factory. The room was held at an optimal mold-growth temperature of 24 degrees Celsius, and contained high-rises of clay vessels. At first, Heatley had the sole responsibility of tending to this mold farm. But later, Florey hired young women to take over this role. Ruth Callow, Betty Cooke, Claire Inayat, Peggy Gardner, Megan Lancaster, and Patricia McKegney were trained by Heatley and later became known as Oxford's "penicillin girls."

Around the same time that Heatley returned to Oxford with his clay vessels, there was a policeman who was in a fight for his life. Albert Alexander was a 43-year-old Oxford police officer in the "septic ward" of the Radcliffe Infirmary, where he had been admitted on October 20, 1940, when a cut on his face had become infected with *Staphylococcus* and *Streptococcus*. The doctors gave him large doses of sulphydryl, an antibacterial medication, but he wasn't improving. By Christmas, his infection had spread to the point that his left eye had to be removed, and x-rays were showing that *osteomyelitis*, or bone infection, was developing in his leg. With nothing to lose, Alexander was more than willing to be penicillin's first human guinea pig.

On February 12, 1941, Alexander was injected with 200 milligrams of the new antibiotic. He didn't have a bad reaction to it, so he was then given 100 milligrams every three hours. Within a day, his condition markedly improved. From his blood work, however, it became clear that the penicillin did not stay in his body long. Just a few hours after an injection, there was only a trace of penicillin left in his blood. Keeping

penicillin in his body was like filling a bucket with a hole. To make matters worse, Florey and his team were running out of penicillin. So they collected Alexander's urine, re-extracted the penicillin from it, and then injected this recycled penicillin back into his body.

By February 16, Alexander seemed to be escaping the grasp of death and was slowly feeling better. But there was a new problem. The penicillin cup-

When designing his new penicillin culture vessel to be fashioned from clay, Heatley borrowed the best features from the bedpan that had inspired him.

board was now completely bare. The amount of penicillin recovered each time from Alexander's urine was less than half of what had been injected, and each subsequent extraction yielded even less. Now there was nothing left. With that, they had to wait to see if what had been done was enough. For 10 days, Alexander seemed to be on his way to a second chance. But on the 11th day, he took a turn for the worse. On March 15, nearly a month after his first injection of penicillin—and hope—Alexander was dead.

Making It Big

This heartbreak made it abundantly clear that the broth under the mold had to be manufactured in massive amounts. In 1941, Heatley and Florey clandestinely flew during the war to the United States with a mission to convince American companies to manufacture penicillin. America was not yet in the war, so American resources were available to create the drug by the tankful. After a meeting in Washington, D.C., Florey and Heatley headed to the National Research Laboratory located in Peoria, Illinois. This newly established laboratory was part of the U.S. Department of Agriculture and had the much-needed fermentation experts and equipment to scale up the process. Here, the lessons Heatley had learned in creating his pilot penicillin factory had to be translated and

modified for large-scale production in the United States. One issue that plagued Heatley was how to increase the yield of penicillin from the mold. While living and working in the corn belt of America, Heatley learned about the manufacture of cornstarch and its thick, gluey by-product called corn steep liquor. When this by-product was added to the broth, the yield of penicillin increased tenfold.

After more than a year in the United States, Heatley's know-how, along with Florey's persistence and charm, got several American drug companies (such as Merck, Pfizer, and Squibb) to create massive doses of penicillin. The first American civilian to receive a life-saving dose was Anne Miller, who was suffering from a deadly infection after childbirth. Penicillin entered the public's consciousness later, on November 28, 1942. Headlines that day were full of reports of a massive fire at the Cocoanut Grove nightclub in Boston, after which many people were treated with a secret drug. That drug was penicillin, which went on to save millions of lives.

For this achievement, Fleming, Florey, and Chain would be awarded the Nobel Prize for Physiology or Medicine in 1945. But not Heatley! He was the unfortunate fourth man. For more than a generation, history failed to recognize him. Although many knew how this scientific odyssey had begun with an interloping mold in a petri dish, few understood that it was actually Heatley's ingenuity in coaxing and mass producing its life-saving elixir that would make our world a safer—and healthier—place.

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A Measure of Trust

Meticulous measurements help make science (and scientists) trustworthy.

Robert T. Pennock

Scientists like to measure things. Doing so is part of what it means to be meticulous in the gathering of evidence. It has often been said that science *is* measurement. The adage that “To measure is to know” is usually traced back to 19th-century physicist William Thompson. Better known as Lord Kelvin, the units of the absolute temperature scale are named kelvins in his honor. Qualitative impressions of feeling cold, warm, or hot are good enough for many daily decisions, but an objective scale makes knowledge more precise, enabling new sorts of discoveries. We now know that there is a minimum possible temperature—called absolute zero, written as 0 kelvin—and likely a highest one as well. Kelvin’s original statement about measurement and knowledge, given in an 1883 lecture, was similarly nuanced, recognizing degrees of knowledge:

I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.

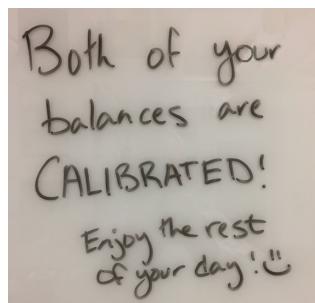
Meticulous measurements are part of what makes scientific findings trustworthy. Science’s core value of evidence-based reasoning and the demonstrable success of its methods is one reason that it has long been among the most trusted institutions.

Recently, however, broad political attacks have generally reduced public

trust in institutions, and science has not escaped the resulting erosion of trust. It is no surprise that scientists have responded to such concerns by trying to find ways to measure public trust and to understand the factors that determine its levels.

Trust Metrics

Trust is a complex notion. One may *trust in* some person, or *trust that* something will occur. Even when not specified, a conviction of trust implicitly involves some object and end; one trusts someone



In scientific research, accurate measurement can provide a kind of geeky happiness.

or something with regard to some purpose: X is trustworthy for P . Depending on the nature, salience, and significance of P , stricter or weaker standards for X may be expected to warrant trust. Consider a simple example: thermometers. Like other tools and instruments, thermometers are more or less trustworthy depending on their properties, in this case properties related to measurement of temperature for different purposes. Several properties are relevant to the warranted level of trust.

Accuracy refers to a measurement’s degree of correctness. The common mercury thermometer mounted outside your kitchen window is sufficiently accurate for determining whether you’ll need to wear a sweater. Tolerance refers to total allowable measurement error, a plus-or-minus deviation from a specified value. Being a few degrees off won’t matter much for picking outerwear, but one needs higher accuracy and smaller tolerances for medical thermometers, because small differences in core body temperature can be significant for diagnosis. Industrial thermometers, when needed to maintain operating conditions to ensure the interchangeability and reliability of manufactured parts, must maintain accuracy and tolerance in harsh factory environments, so durability is an additional required property. To increase instrument reliability requires calibration, which involves comparison and adjustment relative to a known standard.

Because their work depends upon precise, repeatable measurements, scientists and engineers are obsessively meticulous about such matters. Having an instrument that will give trustworthy measurements provides a geeky happiness. I couldn’t help but grin at a message that was neatly written on the white board of a lab I toured when giving an invited talk at another university: “Both of your balances are CALIBRATED!” it read, “Enjoy the rest of your day!” followed by a beaming smiley face.

Measuring Humans

For both qualitative and quantitative research, the goal is to devise an instru-

The trustworthiness of scientific findings increases when they are based on meticulous measurements that are demonstrably accurate, repeatable, and reliable.

QUICK TAKE

An erosion of trust in science has led researchers to develop varied rigorous instruments to quantify and measure this trust and the factors that determine its level.

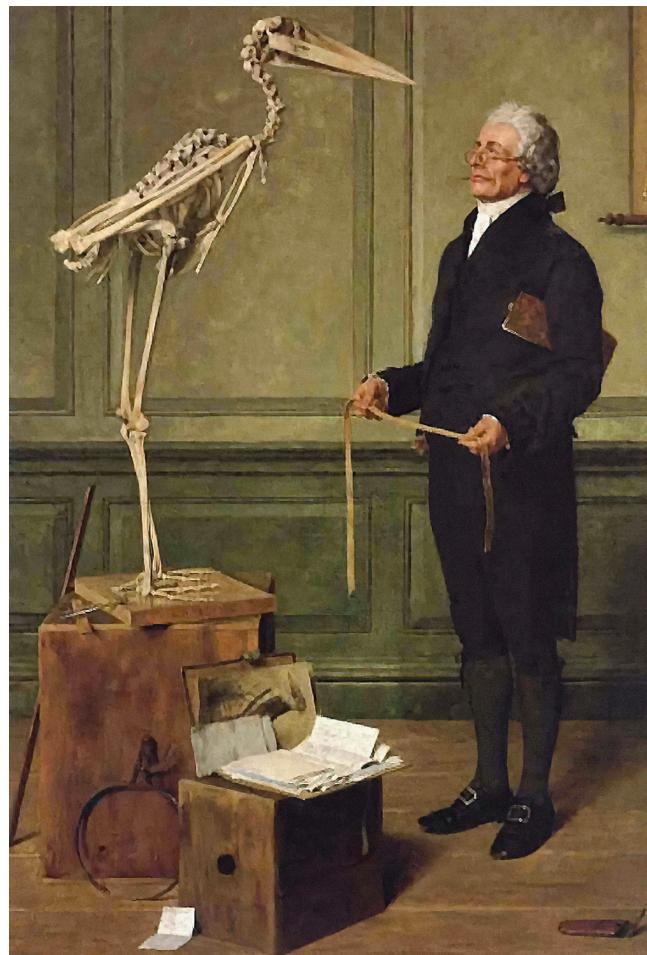
Longitudinal data sets gathered over decades complement cross-sectional data to provide a more nuanced understanding of how public attitudes change.

ment that gives measurements that are both *repeatable*, meaning that others can get the same results when using it under the same conditions, and *reliable*, meaning that its measurements are consistent and also accurate. Quantitative scales have various advantages, such as making comparisons easier over time or across groups. They allow more rigorous statistical analysis that can determine if some difference seen between groups is likely to reflect a real difference rather than an artifact of bias in the sample. In social science instruments, calculating statistical margins of error and confidence intervals can be even more important, to avoid drawing conclusions that are more precise than the data warrant. And properties that interest social scientists—human attitudes or psychological traits, for example—are nuanced and harder to pin down. Survey instruments need to be designed for *validity* in the sense of measuring what is intended.

Human attitudes of trust in science involve a constellation of related elements, so a variety of measures are required to get a meaningful understanding of public attitudes and how these can change over time in relation to other factors.

Promise and Perils

Public feelings of trust or distrust are rarely about scientific methodology *per se*, but rather are intertwined with attitudes about the technological products of science. One dimension of this attitude reflects the belief that science and technology have provided benefits to society and will continue to do so; think of how antibiotics, electricity, water purification, and such have increased human well-being, and the promise of similar beneficial technologies to come. A second dimension reflects reservations about the effects of science and technology to which people may be vulnerable; examples range from the perils of the atomic bomb and anthropogenic climate change, to recent concerns about CRISPR-based genetic engineering.



An 1879 painting by Henry Stacy Marks, titled *Science is Measurement*, captures the idea that one goal of science is to produce trustworthy data using reliable instruments and repeatable metrics.

This aspect of trust in the technological products of science is orthogonal to the basic notion of trust in science and scientists to reliably make discoveries about the natural world. Scientists are not themselves usually the decision-makers regarding applications of their discoveries. Often, their discoveries will be of clear positive human utility and value, but sometimes they will be deleterious.

Similarly, the technologies that arise from such discoveries can have both positive and negative aspects. One may question, for example, whether the benefits of nuclear power outweigh its perils. New technologies such as generative artificial intelligence give rise to reasonable concerns, especially when their consequences are still uncertain. Levels of distrust in this sense of promise or potential peril may rise or fall depending on how such instances play out, which push baseline levels of trust up or down. One way of measuring changes in such attitudes is by cross-sectional studies.

Cross-Sectional Samples

Cross-sectional studies measure properties of groups of interest at a particular point in time. A recent Pew Research Center survey on attitudes of trust collected data from American adults over a one-week period in October 2024. To get meaningful measurements, a survey's sample should be picked from the group of interest in a way that reduces the chance of selection bias. For this study, Pew researchers surveyed 9,593 individuals, recruited through a random national sample drawn from residential addresses, who had agreed to take surveys regularly, to give nearly all members of the target group a chance of selection. A *probability sample* requires that every unit in the population has a known, non-zero chance of being selected. Because Pew's researchers were interested in views of various subgroups of the U.S. adult population, the survey was weighted to be representative by partisan affiliation, education, and various demographic categories.

Concepts of accuracy, tolerance, and so on are applicable in social science research as well. For example, error bars are often included in survey graphs to show the limits of accuracy. The margin of error at the 95 percent confidence level for the Pew study was plus-or-minus 1.3. Tolerance in the context of statistical significance reflects our degree of willingness to draw an incorrect inference, such as concluding there is a difference when there really isn't. Expecting confidence at the 99-percent level is common in the natural sciences, but for human studies, researchers typically must be satisfied with less strict standards. The 95-percent level provides less warrant for precise accuracy but is reasonable for establishing broad patterns and trends.

A series of cross-sectional studies can look at different representative samples of the same population over time to reveal general changes in attitudes in that group. However, such studies are not useful for understanding developmental aspects of such attitudes, such as what factors are most salient in determining people's views over their lifetimes. To

investigate such questions requires a different approach. This type of measurement is the purview of longitudinal studies, which follow the same individuals over time.

A Longitudinal Model
Recently, a research team of which I am a member published both cross-sectional and longitudinal results on attitudes about trust in science. The latter used a remarkable 33-year dataset, collected by team lead Jon Miller of the University of Michigan, to investigate the development of attitudes toward science and technology.

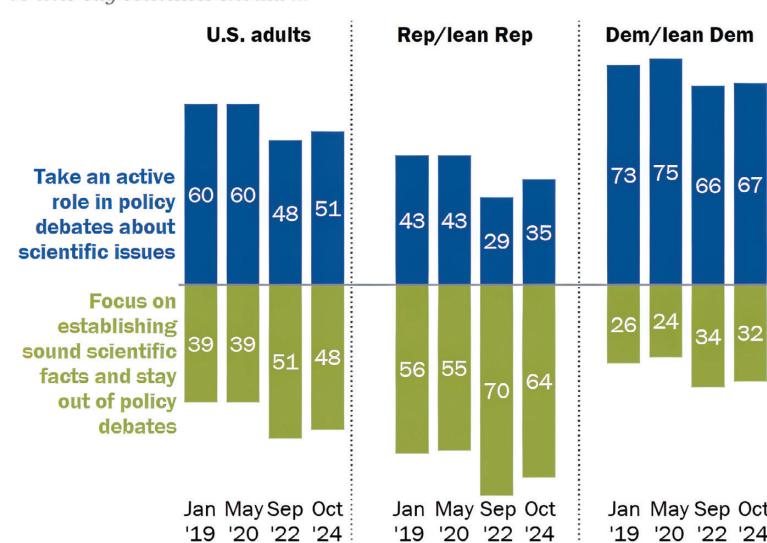
Miller's Longitudinal Study of American Life (LSAL) began in 1986 with a national probability sample of 7th and 10th grade students in American public schools. Among the variables he tracked over the decades for this group are ones related to overall trust in science regarding positive human benefits and harms. This dataset provides a measure of the development of a general attitude toward science and technology by the study participants over the course of their lives, from their teenage years through their mid- to late 40s.

As might be expected, the attitudes of high schoolers are in an early stage of development and not yet clearly constrained. Youth mostly see science and technology in a positive light, with few expressions of concern. Worries about possible negative consequences develop in the 15 years following secondary school. We found a notable difference in attitudes depending on levels of post-secondary education, of both the individual and their parents. Higher post-secondary education and a higher level of scientific literacy were more associated with a positive attitude toward promise and benefit, whereas greater concerns and reservation were associated with lower scientific literacy and a lower level of post-secondary education.

In our structural equation model, religious fundamentalism stood out as

Support for scientists playing an active role in public policy debates is lower now than in 2020

% who say scientists should ...



Note: Respondents who did not give an answer are not shown.

Source: Survey of U.S. adults conducted Oct. 21-27, 2024.

"Public Trust in Scientists and Views on Their Role in Policymaking"

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As part of a larger survey regarding American public trust in science, a study by the Pew Research Center found attitudes on whether or not scientists should weigh in on public policy have fluctuated over time and by political affiliation (Rep indicates Republican, Dem indicates Democrat).

the most significant factor in the shift to increased concerns about science and technology in middle age, probably because contemporary American fundamentalism sees science as part of the modernist worldview it opposes. Reservations about science and technology in the United States increased even further among religious fundamentalists from 2008 to 2020, likely because—as our cross-sectional study showed—political polarization made this perceived conflict a salient issue for more of them.

A full picture of public trust in science requires both cross-sectional and longitudinal measurements. The specific views that new discoveries and technologies may engender—such as attitudes about COVID-19 vaccines or artificial intelligence—arise in relation to general baseline trust attitudes that are developed as part of a lifetime.

Trusting Institutions vs. Individuals

There is a difference between trusting science to find out about the world and trusting that the results of scientific investigations will be aligned with human interests. It is also worth recognizing the distinction between trusting science as an institution or as a method, and trusting scientists themselves. Surveys

that measure trust in scientists consistently show that they enjoy strong relative standing compared with the ratings Americans give most other prominent groups, including business leaders, elected officials, journalists, and religious leaders. Trust in scientists is generally high around the world. Measured on a 5-point scale (in which 1 is very low, and 5 is very high), trust ratings ranged from high-end scores in Egypt (4.30) and India (4.26) to low-end ones that were still largely positive in Kazakhstan (3.23) and Albania (3.05). The grand mean was a moderately high 3.62. These findings are from a new report by a large international team of researchers, led by Victoria Cologna of Harvard University, who

measured trust in scientists in a massive online cross-sectional survey of 71,922 respondents across 68 countries.

General trust in scientists involves views about their competence and character, and for these traits the numbers remain very positive. A recent report by a National Academies of Sciences, Engineering, and Medicine strategic council, convened to examine public confidence in science, highlighted data from an Annenberg Public Policy Center survey, which showed that 80 percent of Americans view scientists as competent, 70 percent as trustworthy, and 65–68 percent as honest, ethical, and caring about the well-being of others. Taken together, such attitudes help account for why 84 percent are confident or very confident that scientists provide the public with trustworthy information about the science in their area of inquiry. Global averages are a bit lower, but still quite high; 78 percent think scientists are qualified to conduct high-impact work, and few think they are dishonest (11 percent) or don't care about others' well-being (15 percent).

Factors that decrease trust involve perceptions of bias: Scientists are seen as less trustworthy if they are thought to be unable to overcome their human,

political, and personal biases. Being meticulous about measurements is one important way that science keeps its research objective. One figure that I take to be especially encouraging is that when individuals are deciding whether to believe a scientific finding, 92 percent believe it is important that the researchers remain open to changing their minds based on new evidence. This evidence-based mindset is the very essence of science, so here scientific values are in alignment with public expectations. Scientists should emphasize that this mindset is their fundamental vocational commitment.

Trusting Scientists in Public Policy

As trust is a relational property—one trusts someone or something for some purpose—another element of public trust in science involves the degree to which scientists are felt to be trustworthy for the purpose of forming public policy. Measurements of this aspect of trust in scientists show more mixed attitudes and, currently, more partisan variability. The recent Pew survey had a special focus on public trust in scientists for this purpose. It showed some significant party-based differences in attitudes.

Two-thirds of Democrats say scientists should be active in policy debates on scientific issues, and 61 percent say that scientists currently don't have enough influence in shaping policy. By contrast, Republicans want more limited engagement by scientists: 64 percent say they should stay out of policy debates. And more Republicans than Democrats say scientists currently have too much policy influence (34 percent versus 22 percent). Across parties, 43 percent describe their influence as about right.

Measured as a whole, the American public is about evenly split on whether scientists should take an active role in public policy debates about scientific issues, or stay out of those debates and just focus on establishing sound scientific facts (51 percent versus 48 percent). The former figure is a three-point up-tick over the 2022 low but still reflects a significant drop from the 60-percent figure prior to the COVID-19 pandemic.

The Disease of Distrust

The measured dip in trust during the pandemic is worrisome because public health policy ought to be based on our best assessments of the facts. If the public loses trust in science to provide the facts, then decision-making

becomes unmoored from reality, to the detriment of everyone.

One factor that has been well-established to have figured in this pandemic drop is partisan politicization. Although overall distributions of scores regarding concerns about science are similar across political lines, suggesting that much of science and technology is still viewed without significant partisan

The American public is about evenly split on whether scientists should take an active role in public policy debates about scientific issues, or stay out of those debates and just focus on establishing sound scientific facts.

bias, there are clear divergences of views for specific topics that have become politically polarized, such as climate change and pandemic public health policies. Historical data show that public trust in science in the United States by political orientation began to diverge slightly in the 1990s, with a dramatic split following the COVID-19 outbreak.

A second, related, hypothesis also deserves attention. Most people get their science information indirectly from science communicators or spokespeople. Only 45 percent of U.S. adults see researchers as good communicators. The simplifications that public health spokespeople make to tell a clear story, for whatever reason, cause distrust when the story changes: Officials telling people to stop buying masks, and then later requiring masking, set them up for loss of credibility. Science communicators may also inadvertently undermine trust by not clearly articulating the degree of uncertainty in the evidence, so that later changes in policy recommendations are seen as inconsistent and a sign that such pronouncements were not trustworthy, rather than a sign that our understanding of the problem was improving as science gathered more data.

As the COVID-era controversies have receded, levels of trust are headed

back up. Now, 88 percent of Democrats trust scientists to act in the public interest compared with 66 percent of Republicans, though the latter represents an increase of 5 percentage points over the previous year. It remains to be seen whether levels of trust will return to prepandemic levels.

Be Measured

Taking the temperature of public trust in science is itself a science. Meticulous measurement is essential for understanding public sentiment, just as it is for other scientific areas. When science is done properly, it deserves our trust in the narrow sense that, through its evidential methods, it provides our best account of the empirical world. Scientists deserve our trust for this purpose when they embody the virtues that support that work. To that end, let us be measured in our judgments and actions. Let us strive to hew to the core guiding values that aim at ascertaining our best measure of understanding of the natural world. A steadfast commitment to this central, guiding purpose is what engenders and anchors science's own reliability and utility. If we do our work with excellence and integrity, our science will be worthy of a full measure of trust.

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Roaming Rocks

Metamorphic minerals are emissaries from the deep, traveling to distant realms and revealing the restless nature of Earth.

Marcia Bjornerud

As geological sites go, this one is easy to miss. It's just a low rise of exposed rock along a back road in northern Wisconsin, outside a town whose one claim to fame is a tavern that the gangster John Dillinger used as a hideout in the 1930s. Even though I've been to this outcrop many times before, I drive right past it on this autumn day and need to look for a place where it's possible for three university vans to turn around. We manage to make the maneuver, come back from the other direction, and park on the shoulder. Students spill out of the vehicles, clearly underwhelmed, puzzled at why we've bothered to stop here. They don't yet realize that this place is a secret portal into Earth's interior.

I urge them to look closely, to get down on hands and knees for a few minutes, use their magnifying glasses, and then tell me what they see. There's a little moaning—they're getting hungry, and we've already seen a lot of rocks today—but everybody complies. Within a minute, I start to hear exclamations that make me smile: "Hey, look at all that biotite! And tons of tiny red garnets! What are those bluish crystals—kyanite?"

The students' initial disinterest turns to respect; they understand that the rocks have taken a journey no human ever could. We've talked in class about

rocks like these: mica schists and their improbable biographies, how they are emissaries bearing news from alien realms. But it's different to see them up close, in their current resting state.

By geological classification, these rocks are *metamorphic*, meaning that they have been transformed under punishing heat and pressure beneath the surface—and then, astonishingly, come back up. Unlike an igneous basalt crystallized from lava, or a sedimentary sandstone laid down by water, metamorphic rocks form in one environment, then go on journeys deep in the Earth's crust. This trek makes them the itinerant travel writers of the rock world, returning to tell us about the restless, animate, hidden nature of the solid Earth. At each stage of their pilgrimage, they preserve a record of their experiences, and through them we can gain a glimpse of inaccessible subsurface worlds—places that humans may never encounter directly.

Inside Information

The metamorphic schists my students and I are analyzing in Wisconsin would have had humble beginnings as mucky, muddy sediments—the weathered residuum of still older rocks—on an ancient seabed. As more sediment blanketed and buried them, these muds lost contact with the hectic surface world, the commotion of wind

and waves. Under the growing weight of the overlying deposits, the mud was compelled to let go of its natal seawater, becoming ever denser and more compact, and finally solidifying into mudstone or shale.

Millions of years pass. The geography of the world changes with the never-ending dance of tectonic plates. One day, the shale finds itself in the vicelike squeeze of colliding continents, folded deep into the interior of a mountain belt. The pressure at such depths is extreme. The fine clay minerals in the shale, now far from the shallow marine waters in which they formed, can no longer hold their shape. Their chemical bonds weaken, their grain boundaries become diffuse, and a remarkable transfiguration begins. The elements within, previously part of a rigid crystal scaffolding, are now free to wander. Atoms of aluminum, silicon, magnesium, and iron, surprised at their unaccustomed mobility, form new alliances and reconfigure themselves as minerals comfortable at these depths and temperatures: shiny black biotite, wine-dark garnet, and sky-blue kyanite.

Intellectually, I understand the cause of metamorphism: It's the thermodynamic imperative for crystals to reconfigure themselves into forms that are stable under new temperature and pressure conditions, in the same way

QUICK TAKE

Metamorphic rocks traveled from Earth's surface to its mantle and back out again. Along the way, they collected evidence of the planet's past and of its inaccessible interior.

For rocks to become metamorphic, they require heat, pressure, and water. Studying the types of minerals in a location can reveal the area's environment millions of years ago.

Plate tectonics moves rocks through the Earth, and they recrystallize in their new environments. Metamorphic rocks are abundant on Earth but are rare in the Solar System.



Gabbro / Alamy Stock Photo

This mica schist made a journey deep inside the Earth before emerging on Mount Healy in Alaska's Denali National Park and Preserve. Metamorphic rocks such as mica schists have sedimentary or igneous origins but are transformed by the temperatures and pressures of Earth's lower crust and mantle. When they reemerge on the surface, their compositions and structures carry clues about the planet's inaccessible interior.

that powdery snow transforms with burial to glacial ice. Still, the process strikes me as deeply mysterious, a kind of natural alchemy. *Metamorphic* literally means “after-formed,” an apt description of these shape-shifting rocks. Prosaic mud reinvents itself as resplendent mica schist, dull limestones transubstantiate into milky marbles, sandstones are reincarnated as luminous quartzites—even though in their subterranean world there is no light to reveal their beautiful new guises.

The mountains that harbored our schists eventually attained their maximum heights, and the tectonic action moved elsewhere. Erosion, intent on enforcing topographic egalitarianism, set to work dismantling them, focusing with special ferocity on the summits in the heart of the range. For the schists, this process was the start of a slow pilgrimage back to the surface. Eventually, they would feel the wind

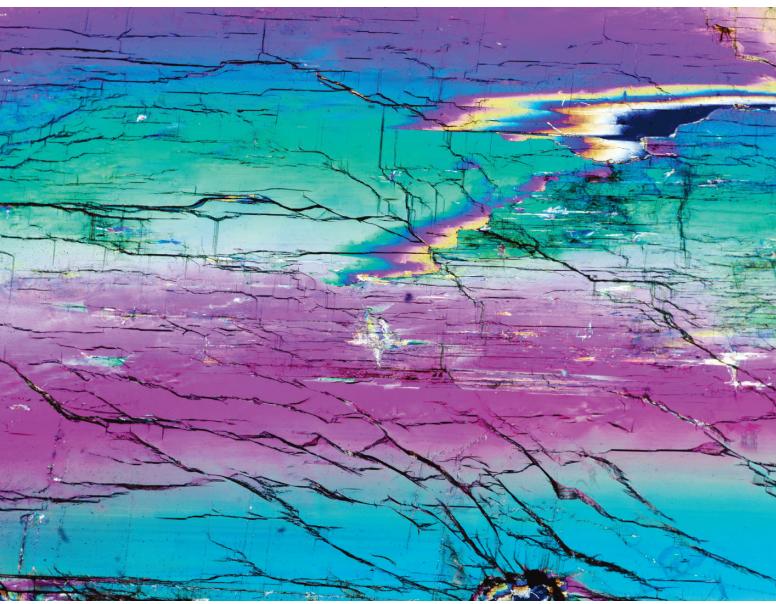
and sunlight again, testifying to anyone listening about the lofty peaks that once loomed here.

I ask my students to recall an earlier stop about 50 kilometers to the north, where we saw some dark-gray mudstones. When I tell them those rocks were the progenitors of these garnet-biotite-kyanite schists—part of the same stratum, but never buried to such depths—they are stunned, and even strangely moved; it's like meeting the same person as a child and as an adult on one day. Knowing what these rocks once looked like makes their journey feel more real and remarkable.

Most people would identify space as the “final frontier,” the last unexplored territory. But consider this asymmetry: High-altitude aircraft routinely fly 15 kilometers above the surface of Earth, and two dozen humans have made the 384,000-kilometer voyage to the Moon. Our satellites now clutter

the outer edge of the atmosphere, and we've sent rovers to Mars. The Voyager 1 spacecraft left our Solar System in 2012 and continues to hurtle into interstellar space. Yet no person has ever been much more than 4 kilometers into the Earth's subsurface (the reach of the deepest mine, a gold operation in South Africa). Even our mechanical proxies haven't gone much further. In a ridiculous Cold War competition, the USSR and NATO countries tried to best each other in deep drilling. The Soviets won that event, with a hole drilled into granites on Russia's Kola Peninsula that managed to reach 12 kilometers before the bit became ineffective, softened by geothermal heat. That's little more than a long walk—about the distance from the north end of Central Park to the ferry terminals at Manhattan's southern tip.

We do have ways of making indirect inferences about the composition of Earth's interior—most importantly, by observing how seismic waves propagate through rocks far below the surface. But the only physical samples we have of the lower crust and mantle are metamorphic rocks, such as our



Dirk Wiersma; De Agostini Picture Library/Science Source

Wisconsin schists, which have spent time at inaccessible depths and then helpfully made the long trek back up to share with us surface dwellers what they witnessed.

In my teaching, I sometimes struggle to convey the weirdness of metamorphism. The three main categories of rock—igneous, sedimentary, and metamorphic—are akin to different literary genres. Igneous rocks are like action-packed thrillers, telling dramatic tales of volcanism and roiling magma chambers. Sedimentary rocks are serious historical tomes, admirably thorough but sometimes dull. Metamorphic rocks, in comparison, have a much greater range of narrative arcs and defy easy categorization. Their early chapters could be igneous or sedimentary, but then the action veers in a completely different direction, with the mineral protagonists finding themselves in alien territory and having to find ways to adjust. It's as if, midway through a scholarly biography of Lord Nelson, the scene shifts to the seafloor and he becomes Captain Nemo.

Temperature and Pressure Matrix

We've observed metamorphism—technically solid-state recrystallization of rocks—since at least the mid-1800s. However, our modern understanding is usually traced to work done in the 1910s and 1920s. Back then, geologists understood deep time, but they were only beginning to grapple with the idea that an internal engine fueled by radioactive heat animates our planet. It was decades before the theory of

plate tectonics would emerge and provide the explanatory framework for how mountains form and rocks could travel to new environments.

In the Scottish Highlands, geologists were mapping a complexly deformed sequence of sedimentary rocks called the Dalradian Series. We now know that these rocks record the growth of the hemisphere-scale Caledonian-Appalachian mountain chain during

**Like explorers
carefully keeping a
log of their latitude
and longitude,
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in pressure-
temperature space.**

the assembly of Pangaea, but in the early 20th century, when continents were thought to be rooted in place, the global context of the Highland rocks was not understood. During their mapping of the Grampian Region, geologists carefully recorded the minerals in a metamorphosed mudstone, including biotite, garnet, and kyanite—the same colorful characters my students recognized in the Wisconsin schist.

At the time, geologists thought that metamorphism was caused solely by



The metamorphic minerals kyanite (left) and andalusite (above) have the same chemical composition, but different conditions during their creation resulted in distinct crystalline structures. Both minerals are formed when sedimentary rocks encounter the high temperatures of Earth's interior; however, kyanite's comparatively denser structure indicates that the mineral experienced high pressure as well.

heat. So it was a surprise when they found no kyanite in similarly heated Dalradian mudstones just to the northeast, in Scotland's Buchan district. Instead, the Buchan rocks were dotted with a cream-colored mineral called *andalusite*, which sometimes occurs in the shape of a stubby cross. Why the difference? This geologic mystery seemed akin to putting two cakes made with the same batter in the oven at the same time and emerging with completely different flavors.

One clue was that andalusite and kyanite have the same chemical composition and formula— Al_2SiO_5 —but different crystal structures. They are polymorphs of each other, in the same way that graphite and diamond are both crystalline varieties of carbon but with distinct molecular forms. A second important observation was that kyanite is significantly denser than andalusite, indicating that its crystal structure is more compact—and formed under greater pressure. This realization was the solution to the Dalradian mystery: Metamorphic reactions, and the metamorphic minerals that record them, are functions of both temperature and pressure.

Around the same time in the 1910s and 1920s, working independently, the Finnish geologist Pentti Eskola came to the same conclusion as his British counterparts. Based on his deep knowledge of the Baltic Shield's geology, Eskola plotted the relative positions of various metamorphic rocks on a graph of pressure versus temperature, creating the first, rough metamor-

phic phase diagram. He anticipated a time when the *stability fields*—the native habitats or “comfort zones”—of metamorphic minerals could be determined quantitatively, and the obscure dialects of metamorphic rocks could be translated.

A century later, Eskola’s vision has been achieved. It’s now possible to simulate the high pressure and temperature conditions of metamorphism in laboratory experiments and coax tiny amounts of minerals such as garnet, kyanite, and andalusite to form. We now have detailed metamorphic phase diagrams for rocks of all starting compositions, and their travel itineraries can be reconstructed in detail.

Some metamorphic reactions—such as the conversion of graphite to diamond—are primarily sensitive to pressure, with temperature playing only a secondary role. These reactions are known as *geobarometers* because the presence of one mineral or the other tightly constrains the pressures that the rocks endured. Conversely, temperature-sensitive but pressure-independent reactions are *geothermometers*, reliable indicators of past temperatures. Like explorers carefully keeping a log of their latitude and longitude, metamorphic rocks thus record their coordinates in pressure-temperature space. This information, in combination with methods for dating minerals using natural radioactivity, makes it possible to track metamorphic rocks in space and time. Eskola would have been pleased and astonished.

Metamorphic Conditions

Under the microscope, metamorphic rocks are like exquisite illuminated manuscripts, with interlacing minerals chronicling their hidden, subterranean experiences. Crystals that grew in distinct episodes over time will develop concentric bands like tree rings, and early formed minerals may be engulfed or rimmed by later ones. On the way to becoming schist, a mudstone might first have been a slate, and garnets that overgrew the slate’s aligned minerals can preserve a record of that stage even when the slaty texture has been erased in the rest of the rock—like a tree that grew around the wires of an old fence that has long since been removed.

Microscopic observations, together with laboratory experiments, have also shown that fluids in the crust—mainly water, but also carbon dioxide, and

various elements dissolved in these phases—are as important as temperature and pressure in governing metamorphic reactions. Water’s presence dictates the temperatures and rates at which reactions occur, and on a watery planet this is the rule rather than the exception. Indeed, the one important scientific result of the absurd and expensive Cold War race to drill the deepest hole was the discovery that water (in a supercritical form, neither liquid nor gas) occurred even at the greatest depths reached.

Some of my own work in western Norway—another part of the great Caledonian–Appalachian mountain chain—has shown that, in the complete absence of fluids, metamorphism may not happen at all. Just north of Bergen,

Water-mediated metamorphism is the key to plate tectonics, which rejuvenates topography, replenishes the atmosphere, and keeps the planet in a constant state of renewal.

rocks that were once deep in the heart of that great mountain range are exposed on the ice-scoured and wind-swept island of Holsnøy. Tiny Holsnøy is disproportionately famous among geologists because it provides a kind of counterfactual glimpse of an Earth in which crustal rocks are devoid of water.

The rocks on Holsnøy have the composition of basalt, the rock that makes up the ocean crust. They experienced two distinct mountain-building events, one about 900 million years ago and another around 400 million years ago—and in both cases were subjected to extreme metamorphic conditions. During the first event, the rocks experienced moderate pressures at a depth of 25 kilometers, but very high temperatures—close to their melting point—so hot that all water in hydrous minerals was baked out, leaving an exceptionally dry rock mass.

Five hundred million years later, these parched rocks found themselves

even deeper in the crust—more than 45 kilometers down—but at less extreme temperatures. At such depth, they should have completely converted, via metamorphic recrystallization, to a dense, improbably beautiful rock called *eclogite*, with raspberry garnets set in a field of grass-green pyroxene (and a particular favorite of Eskola’s). But, oddly, eclogite on Holsnøy occurs only along narrow zones and bands constituting perhaps 30 percent of the rock mass. The eclogite-forming metamorphic reactions were for some reason frozen in action, leaving converted and unconverted rock in juxtaposition and providing a rare, close-up view of the metamorphic processes that happen too deep in the crust for us ever to witness.

How could the rocks on Holsnøy have ignored the thermodynamic edict, under very literal pressure, to recrystallize entirely to eclogite? The answer seems to be the extraordinary dryness of the rocks at the time they were at eclogite-forming depths. Without water, atoms can move through rocks only by the arduous process of diffusion, which is tortuously slow, like driving a car in urban gridlock. Metamorphic reactions in the complete absence of water would be so sluggish that they would not happen even on geologic timescales. In contrast, when water is present, atoms can slip into solution and hitch a ride, akin to hopping on the subway and moving swiftly through the city. Transported quickly to new sites, the elements in rocks can easily reorganize themselves, and build minerals that are stable under the new conditions.

We think that, on Holsnøy, eclogite-forming reactions were suppressed by the lack of water until several large earthquakes shattered the unusually dry rocks and allowed limited amounts of external fluids to enter along fractures, forming the localized deposits of eclogite that are so odd and remarkable. Equally remarkable is the fact that these rocks ever made it all the way back to the surface, via tectonic uplift and tenacious erosion, to be marveled at by human pilgrims.

Rocky Journey

This story about weird rocks from a remote place might seem arcane, but it illuminates some fundamental truths about Earth’s plate tectonic system, and in particular its signature process of



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Rocks of basaltic composition on the Norwegian island of Holsnøy experienced the temperatures and pressures necessary to create new metamorphic minerals, but the rocks did not completely transform. Geologists speculate that dry conditions kept the elements from moving and crystallizing into new forms. Eclogite (inset), a metamorphic rock, is found only in localized areas of the island, where earthquakes allowed water to seep into the Earth's interior and interact with the basaltic rocks.

subduction. Along subduction zones, such as the one sitting off Japan's east coast, basaltic ocean crust plunges into the mantle. Subduction of the ocean floor is Earth's brilliant recycling and rejuvenation system, and without it our planet would be utterly different.

However, slabs of ocean crust would be too buoyant to sink very far into the mantle if they did not convert to their much denser metamorphic form: eclogite. To me, one of the strangest things about Earth is that basalt—which is derived from the mantle—can be recrystallized at high pressure into eclogite, which is *denser* than the mantle. Our work on Holsnøy suggests that, in the absence of water, the basalt–eclogite conversion would not happen, deep subduction would be impossible, and the planet's tectonic system would be entirely different. Water-mediated metamorphism, in other words, is the key to plate tectonics, which rejuvenates topography, replenishes the atmosphere, and keeps the planet in a constant state of renewal.

More generally, given the crucial role of water in their formation, met-

amorphic rocks of any type (except those created by brute force in meteorite impacts) may be unique in the Solar System. And in the absence of plate tectonics, which is also unique to Earth, opportunities for rocks to travel to new environments, and thereby be transformed, would be limited anyway. Moon rocks collected during the Apollo missions, and rare meteorites that have come to us from Mars, attest to harrowing bombardment by space debris but have no stories to tell about adventures on their own worlds. Despite their long trips to Earth, these rocks are strangely naive, inexperienced.

Only Earth rocks have had the chance to study abroad, wander the globe, dive into the crust, and recreate themselves. In fact, metamorphic rocks are actually the dominant type on Earth, because most rocks, if they are around long enough, will find themselves in new environments.

It is our good fortune to have such an abundance of metamorphic rocks in our midst, with insights to share not only about their origins but also about everything they've experienced since.

It's not too much of a stretch to say that they are responsive, even sentient, in that they "perceive" their surroundings and change in response. Their stories are genuinely epic: The journey of a rock like our Wisconsin schist from the surface to the center of a mountain belt and back echoes the narrative arc of katabasis and anabasis in Greek myth: the protagonist's descent into the Underworld, the tribulations experienced there, and the eventual return, with hard-won wisdom, to the land of the living.

Metamorphic rocks embody the animate, resilient, creative nature of the solid Earth. For us mortal Earthlings, they speak of the possibility of reinvention, the beauty of transformation—and the ephemerality of any particular version of the world.

It's getting late, almost time to leave. In the slanting rays of the late afternoon sunlight, a sense of serenity fills me as I watch students crawling across this easily missed outcrop of mica schist on their hands and knees, like supplicants approaching a holy shrine.

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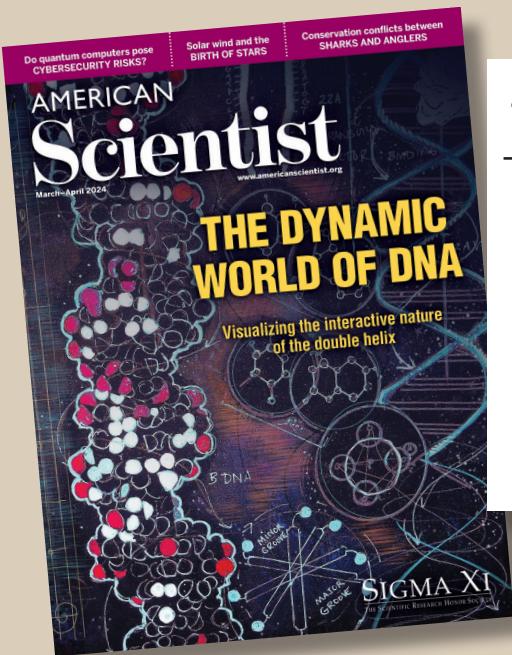
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Consciousness: The Road to Reductionism

Neuroscientific evidence increasingly shows that consciousness is a remarkable but explainable function of a machinelike brain.

Alan J. McComas

The cathedrals of Chartres and Notre Dame; particle colliders that sift the building blocks of matter and energy from the chaos of smashed atoms; artificial intelligences that in some respects outperform their creators. All of these marvels were conceived by the human brain, a complex structure weighing a mere 1.5 kilograms. But this remarkable organ also gives us something else that we often take for granted—our sense of self.

We each possess a consciousness that seemingly enables us to feel and think, to act, to remember, and to envision the future. Although consciousness is inextricably linked to our identity, it can oddly also feel like a separate but connected being inside of us—an observer that is not only aware of us and our surroundings, but that also provides verbal commentary throughout our waking hours.

It's no wonder, then, that many ancient priests and philosophers took the mystical view that consciousness is conferred upon us or somehow arises from outside the body. What is more surprising is that such views continue despite enormous advances in neuroscience. Their persistence deepens the need for a clear exposition of a *reductionist* approach, which views consciousness as a function of the brain—a biological machine whose workings can be understood by an examination of its parts. This model is based on contemporary neuroscience and is aided by advancements in our ability to record impulses from single human neurons, including

those parts of the brain most involved in generating consciousness.

Hence, my earlier use of the term “seemingly” when describing our perception of consciousness: We believe that we run the operation—that we decide to act, remember, direct our attention, and so on; but in each case, neural activity in the brain precedes our conscious awareness of these tasks, and activity in areas concerned with memory precedes our knowledge of self. Arriving at these conclusions has been a long road and has required challenging cherished dogmas, both religious and scientific. Though significant questions remain regarding how our brains create certain subjective experiences, each new discovery helps us better understand ourselves.

Probing the Thalamus

As a medically trained neurophysiologist in the 1960s, I accepted the widely held view that, given the tools then available, the nature of consciousness was too complex a problem to reward investigation. Then a promising opportunity arose with the advent of new treatments for patients with Parkinson's disease who had uncontrollable hand tremors, as well as for cancer patients with intractable pain.

Both treatments involved destroying small groups of neurons in the *thalamus*. The thalamus is the large collection of nerve cell clusters atop the brain stem that passes information on to the *cerebral cortex*, the brain's highly developed outer layer that is associated with functions

such as decision-making, language, memory, perception, and thought. To understand the functions of specific regions of the cortex, researchers, including myself, would study the effects of damaging them. We used a narrow liquid-nitrogen probe to freeze precisely targeted areas.

At the time, we often struggled to localize the treatment targets for diseases like Parkinson's within the brain. The thalamus is a deep structure, and brains differ in size and shape; furthermore, neither computed tomography (CT) nor magnetic resonance imaging (MRI) had yet been invented. The solution entailed probing the thalamus with a tungsten wire electrode sharpened to a point small enough to detect electrical impulses in single neurons. By finding neurons that responded to touch or pressure on the head's opposite side, or to the movement of finger joints, we gained the reference needed to locate the therapeutic target: The cluster of nerve cells, or *nucleus*, whose cells responded to touch, pressure, and finger movement, was situated just behind the one in which we needed to freeze a lesion to stop the parkinsonian tremor (whereas for the patients operated upon for intractable pain, the freezing lesion was made in a different nucleus).

Before making the lesion, we had the opportunity for an experiment on one key aspect of consciousness: perception. We wanted to test a proposal made a few years earlier by British electrophysiologist and Nobel laureate Edgar Adrian

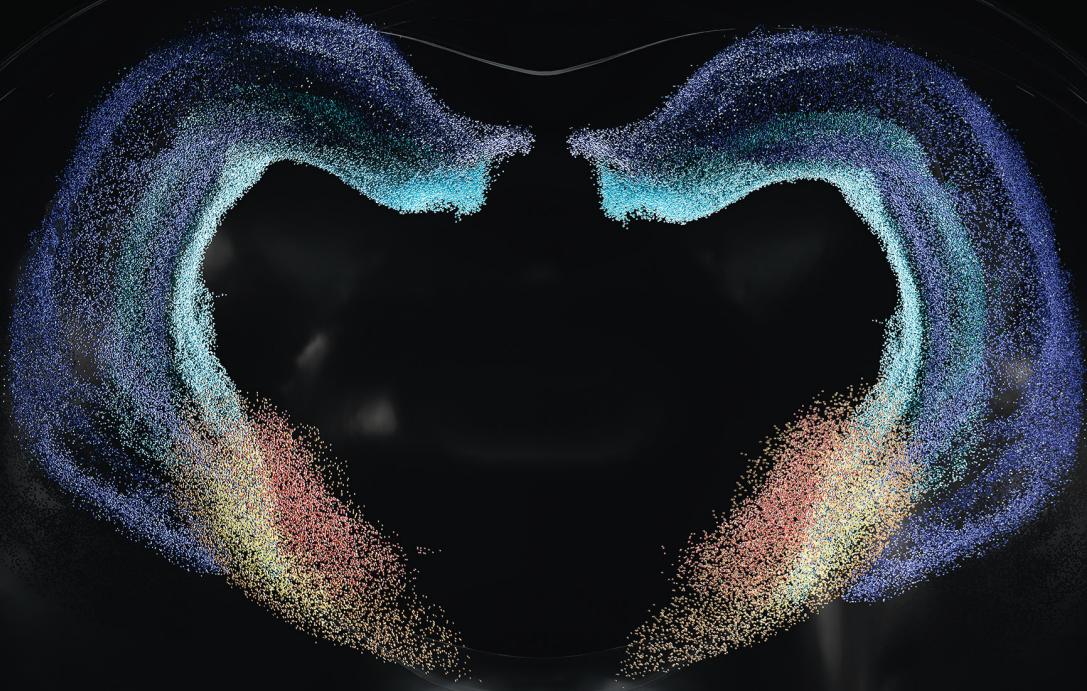
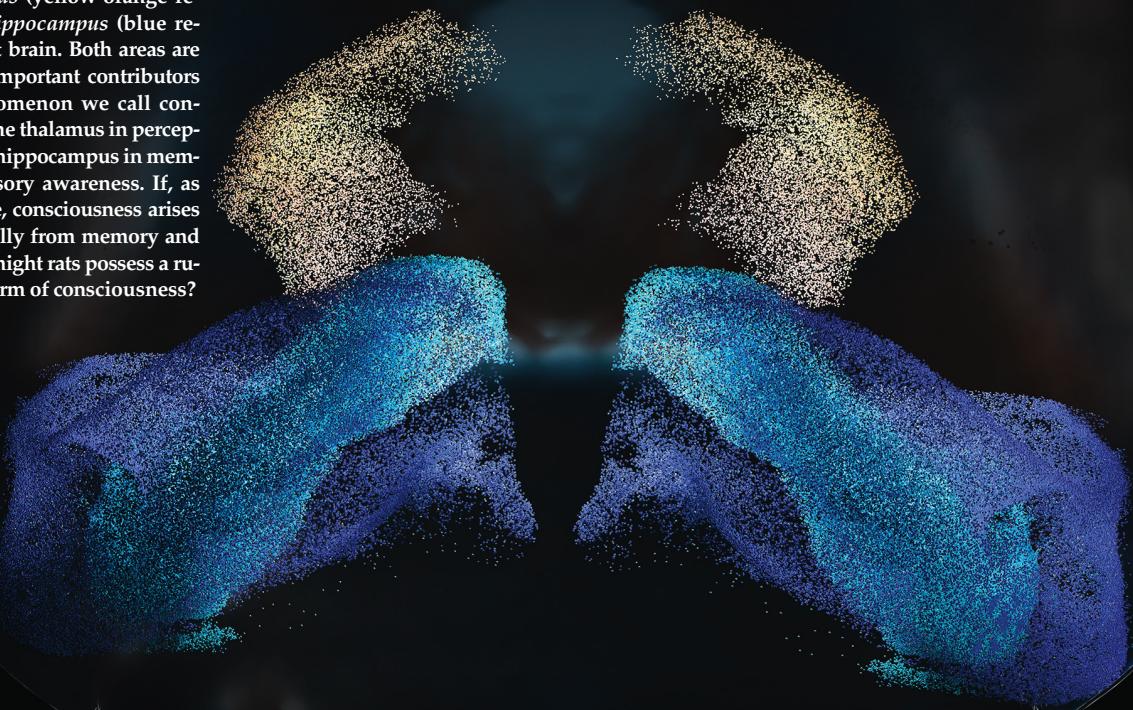
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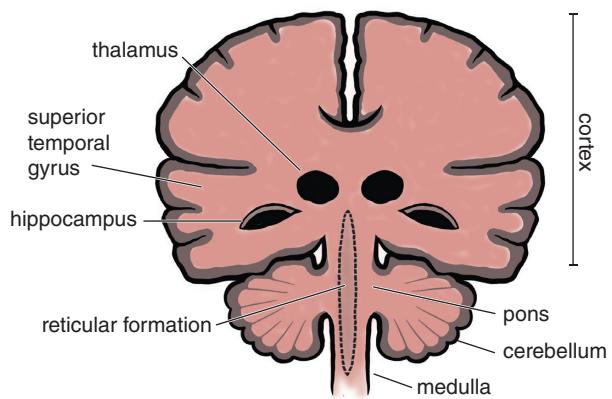
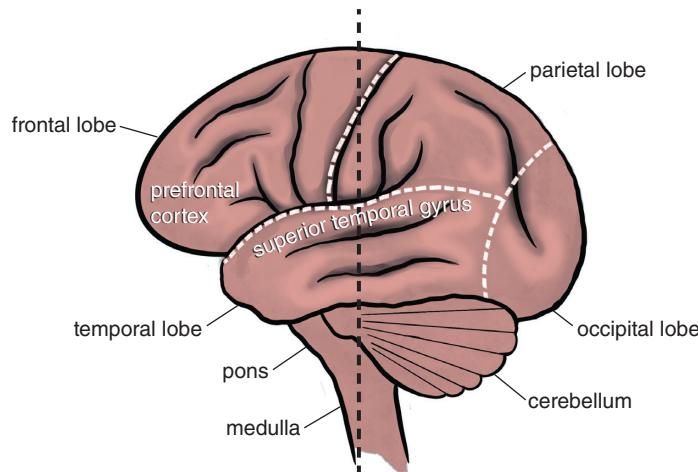
The reductionist view argues that consciousness requires no mystical explanation but rather is a function of the brain, an organic machine that we can understand through research.

Though we seemingly choose our actions, studies show that neural firing occurs prior to awareness and that activity in the brain's memory areas precedes our knowledge of self.

The seat of consciousness may not be the cerebral cortex but rather ancient brain areas that manage memories and concepts—areas humans share with other animals.

This data visualization shows the distribution of neuron cores in each *thalamus* (yellow-orange region) and *hippocampus* (blue region) of a rat brain. Both areas are considered important contributors to the phenomenon we call consciousness: the thalamus in perception and the hippocampus in memory and sensory awareness. If, as some believe, consciousness arises mechanistically from memory and perception, might rats possess a rudimentary form of consciousness?





This lateral view (left) shows the areas of the human brain together with the principal grooves (*sulci*) and folds (*gyri*) in the *cerebral cortex*, the outermost layer of mammalian brains. The *prefrontal cortex* was long a site of interest in consciousness research and models. The *superior temporal gyrus*, home of the auditory cortex, might also be the site of auditory memory, which some reductionists believe is the source of our perceived inner voice. The coronal (transverse) section of the brain (right) corresponds to the vertical dashed line in the left illustration; greatly simplified, this figure shows several deep structures relevant to consciousness, including the thalamus (important in understanding perception), the hippocampus (essential to memory and to turning sensory input into conscious awareness), and the *reticular formation* (vital to our ability to mindlessly perform familiar tasks, even complex ones). Neuroanatomists were surprised to find that the *cerebellum*, which exhibits no known function other than to remember movements and to make them smoother, contains four times as many neurons as the entire cerebral cortex.

of the University of Cambridge in England that the well-developed nerve fiber pathways from the cerebral cortex to the spinal cord, brain stem, and thalamus regulated the flow of incoming sensory information. Adrian hypothesized that important and timely information would be allowed onward, whereas unimportant or distracting inputs would be suppressed.

To our surprise, our experimental conditions (such as whether the patient noticed a touch on the skin or was distracted from it by conversation or mental arithmetic) did not affect the firing of the thalamic neurons. This finding meant that, though the thalamus might handle raw sensory input, it did not regulate it; the sorting of that input into data to be attended to or ignored was further downstream, likely in higher brain regions such as the cerebral cortex.

The negative results were disappointing, but the lessons they taught proved relevant many years later when we again considered the nature of consciousness. Our experiments had shown that we could obtain satisfactory recordings from single neurons in a conscious human subject. They had also demonstrated that deducing function from anatomy could be misleading: A fiber bundle connecting two parts of the brain need not indicate an active pathway. Similarly, much of the

brain's ongoing impulse activity might be spontaneous rather than purposeful.

With the advent of a medication called L-Dopa (levodopa) in the late 1960s as an effective treatment for parkinsonism, thalamic neurosurgery ended, so our laboratory explored consciousness in other ways; for example, we studied *backward masking*, whereby a second stimulus, if given soon enough, can block perception of an earlier one, and we suggested what might be going on in the different cerebral cortex layers to explain that phenomenon. We also investigated the neural adaptations of subjects who had lost a hand in an accident. And we drew attention to the brain's plasticity with our work in the *somatosensory* area, the area of the parietal lobe that processes the body's sensory information, including touch, pain, and body position (or *proprioception*).

Maps May Mislead

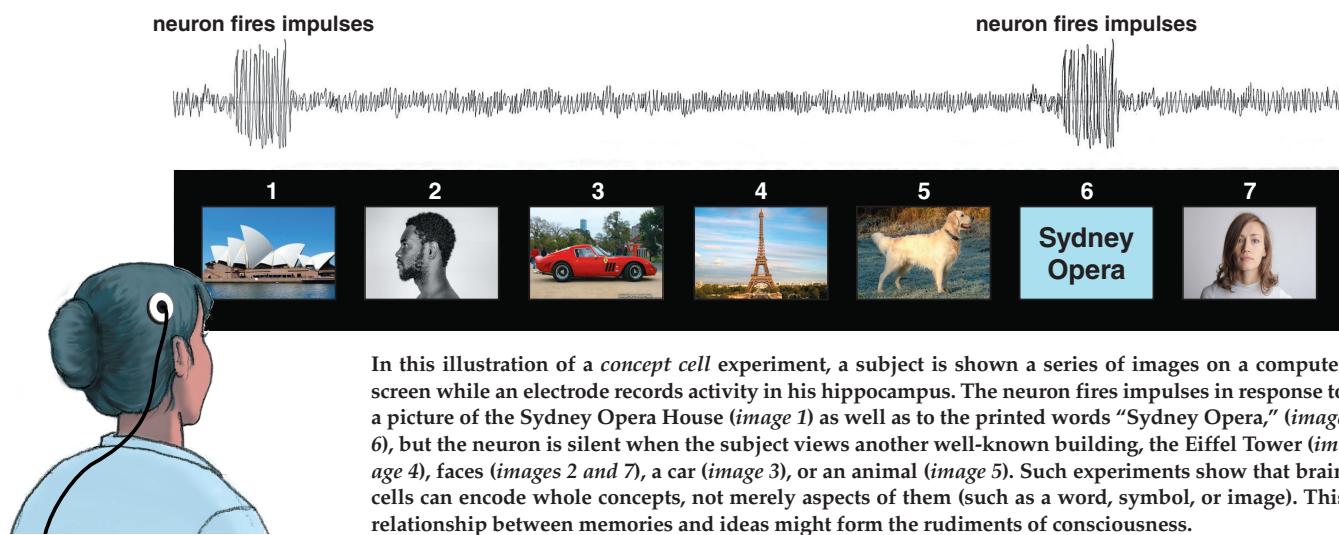
Back in the late 1960s, five beliefs were common among consciousness researchers: consciousness was confined to humans; human consciousness had evolved as the cerebral hemispheres had enlarged; the prefrontal cortex within each cerebral hemisphere was ultimately responsible for consciousness; every part of the nervous system was active and essential; and, most fundamentally, some kind of contentious,

ineffable, and loosely defined *psychical energy* acted on brain neurons and was ultimately responsible for will, attention, and memory recall. (This instinct to seek a spiritual or moral force beyond biological mechanisms is still championed by some.) The present reductionist approach to consciousness offers reasons for rejecting all five views.

The first and second beliefs, the uniqueness and basis of human consciousness, were challenged long ago by Charles Darwin through his extensive observations of animal behaviors. In *The Descent of Man* (1871), he made his position clear:

Nevertheless the difference in mind between man and the higher animals, great as it is, is certainly one of degree and not of kind. We have seen that the senses and intuitions, the various emotions and faculties, such as love, memory, attention, curiosity, imitation, reason, etc., of which man boasts, may be found in an incipient, or even in a well-developed condition, in the lower animals.

Darwin's interest lay not in whether nonhuman animals possessed consciousness—the capacity for emotions, mental states, and basic reasoning—but in what stage of evolution that property had emerged. Yet, despite Darwin's fame and scientific stature, and notwithstanding support from Thomas Huxley and other prominent scientists and thinkers of the time, the idea of animal consciousness dwindled and, lacking a champion, had effectively died by the end of the 19th century. (Exceptions that proved this rule were the notable 20th century work of Donald Griffin of Harvard University and 1973 Nobel laureates Karl von Frisch of the University of



In this illustration of a *concept cell* experiment, a subject is shown a series of images on a computer screen while an electrode records activity in his hippocampus. The neuron fires impulses in response to a picture of the Sydney Opera House (image 1) as well as to the printed words "Sydney Opera," (image 6), but the neuron is silent when the subject views another well-known building, the Eiffel Tower (image 4), faces (images 2 and 7), a car (image 3), or an animal (image 5). Such experiments show that brain cells can encode whole concepts, not merely aspects of them (such as a word, symbol, or image). This relationship between memories and ideas might form the rudiments of consciousness.

Munich in Germany, Konrad Lorenz of the Max Planck Institute for Behavioral Physiology in Seewiesen, Germany, and Nikolaas Tinbergen of the University of Oxford in England concerning "social behavior patterns."

Today, with renewed interest in animal behavior, and with better experimental strategies and monitoring equipment, the situation has reversed. One turning point was the 2012 "Cambridge Declaration on Consciousness" written by a prominent group of international scientists. The Declaration drew from advances in neuroscience and evolving views in bioethics, arguing that emotions and intentions are not solely human provinces—nor indeed do they require a mammalian neocortex. The statement signaled a broader definition of consciousness: "The weight of evidence indicates that humans are not unique in possessing the neurological substrates that generate consciousness. Nonhuman animals, including all mammals and birds, and many other creatures, including octopuses, also possess these neurological substrates."

The other three widespread beliefs among researchers concerned the location and nature of the neural mechanisms essential for human consciousness. Is the whole brain involved or only part? And if the latter, which part? Though many still regard the cerebral cortex and especially the prefrontal areas as the generators of consciousness, some researchers—most notably the late neuroscientist Wilder Penfield of McGill University in Canada—have advanced other candidates over the years.

Penfield was a leading neurosurgeon known for his research on electrical stimulation of conscious patients'

exposed brains. At the Montreal Neurological Institute, which he founded in 1934, Penfield mapped out the cortical areas responsible for movement and touch sensation.

During his clinical work, Penfield made an important observation that conflicted with the view that consciousness was a product of the cerebral cortex and its prefrontal areas. Obliged to operate on his sister for malignant glioma (a tumor of the nervous system), he noted that *resecting*, or surgically removing, the prefrontal area on one side had no discernible effect on her behavior or con-

sciousness. University College London, had done so in a textbook published a century earlier. Similarly, Henry Head, the well-regarded London neurologist and self-experimenter (he had two nerves in his left forearm surgically severed and documented their recovery) had seated consciousness in the thalamus in 1920.

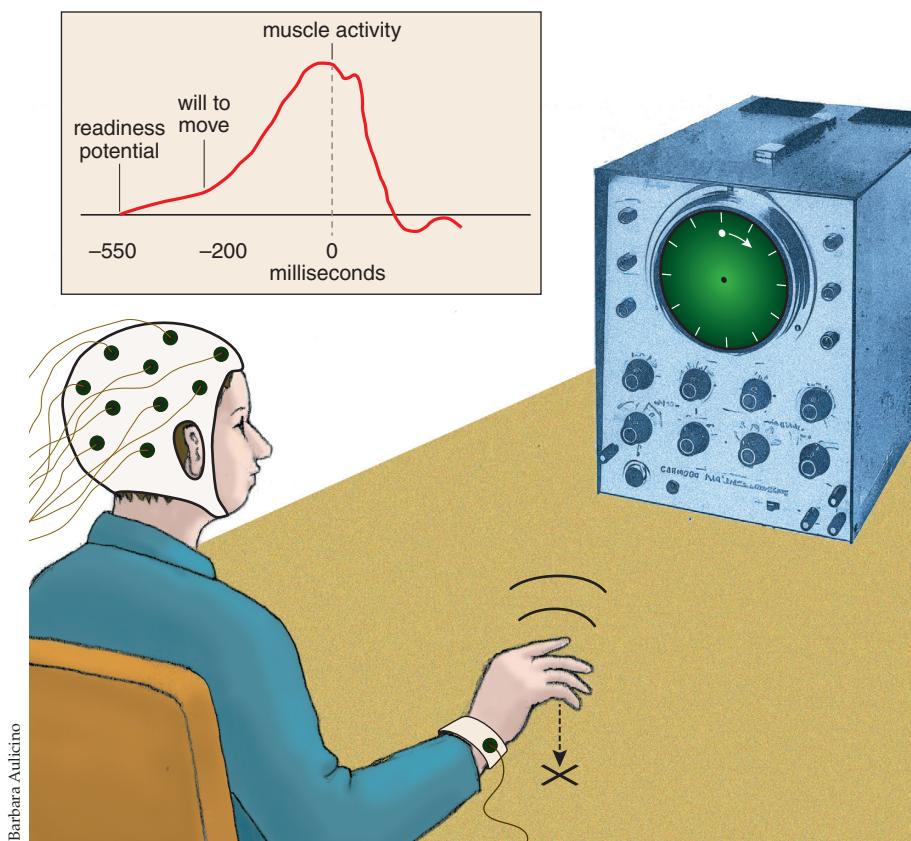
Unfortunately for Penfield, the *centrencephalic hypothesis* fell victim to an overwhelming rebuttal by a highly respected figure in his field, published in the leading neurological journal, *Brain*. Its author, Francis Walshe, was a senior neurologist at the prestigious

These capacities provided evidence for the reductionist view that humans are not dualistic beings—spirits commanding materialistic bodies—but instead are complex automata.

sciousness level. He had witnessed the same lack of effect in patients with damage from head injury, stroke, or tumor elsewhere in the cortex. In contrast, even a modest lesion in the brain stem could result in coma or death.

Penfield proposed that, although the cerebral cortex processed sensory information, consciousness occurred from the integration of that information lower in the brain. Although he had first broached his *centrencephalic hypothesis* in the 1930s, others had advanced similar notions: William Carpenter, a professor of anatomy and physiology at

Hospital for Nervous Diseases in London. With argument, evidence, and rhetorical flair, Walshe dissected the *centrencephalic hypothesis*, arguing that it lacked evidence, downplayed cortical functions in favor of emphasizing the brain stem, and confused correlation with causation. Walshe ended his fusillade with: "The cerebral cortex, of course, could not be wholly ignored, but it is perhaps not unfair to say that it has been stretched upon the Procrustean bed of a preconceived *centrencephalic* system, so that we can scarcely recognize it."



In Benjamin Libet's noted experiment, subjects marked the moment they decided to tap their hands by noting the position of a traveling spot on a clocklike oscilloscope screen. A recording electrode revealed that neural activity buildup, or *readiness potential*, occurred hundreds of milliseconds before the conscious will to move or the onset of muscle activity in the forearm. These results are interpreted by some to mean that intention is not a conscious act.

Although Walshe had not countered all of Penfield's arguments, consciousness had nevertheless been returned to the cerebral cortex, and to the prefrontal areas in particular.

Exploring the Hippocampus

Ironically, it was other intriguing work by Penfield that would start to move neuroscience's seat of consciousness away from the cerebral cortex once again. In the *temporal lobe* (an area on each side of the brain vital to hearing and language comprehension), he had discovered that electrical stimulation could sometimes evoke apparently familiar sounds and images from the patient's past—a strong hint that the temporal lobes helped to mediate memory. In 1953, Penfield took this line of inquiry further when he reported memory loss in patients with temporal lobe damage.

The real breakthrough came when Penfield's colleague, psychologist Brenda Milner, studied an unusual young man who'd had temporal lobe surgery. Largely through Penfield's pioneering work, removal of part of a temporal

lobe had become a recognized treatment for intractable epilepsy, but surgeons only performed the operation on one side. But in the case of this now-famous patient, known as H. M., partial temporal lobe resections—including significant portions of both hippocampi—had been made on both sides (not by Penfield but by prominent American neurosurgeon, William Scoville, in Hartford, Connecticut). Milner easily demonstrated the consequences of the bilateral procedure: H. M. had lost his memories of people and distant events and could retain new information only for some 30 seconds. Although short-term working memory had been preserved, long-term memory had been lost. Further, the key structure affected in the temporal lobe was identified as the *hippocampus*.

Located in the floor of the fluid-filled lateral ventricle, the hippocampus (named for its resemblance to a seahorse) had been little studied. That situation has since changed, as neuroanatomists and neurophysiologists have probed its unusual structure and

function in increasing detail. By 1991, enough research had been amassed regarding the brain area to justify its own scientific journal, the monthly *Hippocampus*. However, it was not until 2005 that neurosurgeon Itzhak Fried of the University of California, Los Angeles, and his colleagues reported in the journal *Nature* that the hippocampus plays a central role in recognition and memory formation—a neural model with strong implications for how sensory input becomes conscious awareness.

Considering Concept Cells

Like Penfield before him, Fried had a special interest in stimulating and recording the brains of epileptic patients as part of their evaluation for surgery. However, recording from single hippocampal neurons with fine wire electrodes was difficult; unlike the thalamic recordings described earlier, the small hippocampal impulses were swamped by the dense spontaneous impulse activity of the many neurons surrounding the electrode tip when it was placed in this area of the brain. The difficulty was overcome when a young Argentinian computer scientist, Rodrigo Quian Quiroga, joined Fried's team and wrote a program that could distinguish the activities of single neurons.

Working on the assumption that the hippocampus dealt with memory, the investigators devised an experiment. As shown in the figure on page 99, a subject would view a computer screen on which a series of images of familiar people, everyday objects, or well-known buildings appeared, each for one minute. If a hippocampal neuron responded to a particular image, researchers would present another series that included modifications of the image. Sometimes they would supply a spoken or written word in its stead.

The results were astonishing. A hippocampal neuron would respond to a certain person, place, or object while ignoring others. Further, the image's details did not seem to matter. Whether the person in the image was looking at the camera or away from it, dressed in different clothes, or sporting short or long hair, made no difference. Remarkably, in some instances the same neuron would still fire if, instead of an image, researchers substituted the written or spoken name signifying the person, object, or place. (Although the experiment measured activity in a single cell, there are in fact thousands

of cells associated with each memory.) Here was credible evidence of the role of hippocampi not only in memory, but in the kind of holistic conceptualization associated with consciousness.

Because the hippocampal neurons responded to distinct aspects of a single item, their discoverers named them *concept cells*. New name notwithstanding, concept cells were in fact the same “grandmother” cells posited by earlier neuroscientists: cells highly specialized to respond to complex stimuli such as recognizing a specific person (the subject’s grandmother, for example). Other neuroscientists had strongly supported an alternative view in which cells in various brain areas responded to different components of sensory information; they had argued that conscious perception occurred only when the distributed cells fired together in a rhythm.

The discovery of concept cells settled that argument and revolutionized the study of memory; it also brought an understanding of consciousness mechanisms very much closer. Already, several observations and arguments linked consciousness to memory. This function was not humanlike consciousness, which is much more than memory and incorporates qualities such as various senses, imagination, inner speech, creativity, and the sense of self. For a simpler-brained creature, even one whose brain is marvelously complex in other ways, a basic memory and sense of “pleasure” would compose the sum of its primordial consciousness—an experience we can no more grasp than we can know “What is it like to be a bat?” (to borrow from an influential 1974 paper by philosopher Thomas Nagel). But we can also be confident that consciousness did not suddenly appear in evolution, but rather started small and has reached its greatest complexity in humans. Thus, during evolution, the existence of memory (specifically, the ability of earlier animals to remember the types and locations of food sources) implied the presence of a nascent consciousness.

Another argument for the role of memory and not just perception in forming consciousness is that, unlike instant awareness, there is no such thing as instant consciousness. On waking from sleep, we need a moment to remember who and where we are, especially if we spent the night in unfamiliar surroundings, as is beautifully described by Marcel Proust in the *Swann’s Way* volume of his 1973 novel

In Search of Lost Time. I once experienced something similar when I was recovering from COVID-19: I woke up and for a moment, frighteningly, had no knowledge of who I was. It is memory that automatically provides that knowledge of self that conscious-

These capacities provided foundational evidence for the reductionist view that humans are not dualistic beings—spirits commanding materialistic bodies—but rather a specialized and complex form of automata. But first, we needed a clearer under-

The brain’s electrical activity appeared some 350 milliseconds before the subject became aware of the intention to tap. It appeared that neural activity had preceded conscious awareness.

ness requires. This distinction between being awake and being fully conscious turns out to be crucial.

The Reticular Activating System

Both the arousal of the brain from sleep and the brain’s continued wakefulness arise from the firing of neurons deeply situated in the brain stem’s *reticular formation*. In this complex arrangement of cell bodies and fibers, groups of nuclei can be distinguished only with difficulty under the microscope. Two of these nuclei, the *locus coeruleus* and the *giant cell nucleus*, appear to be the main components of the *reticular activating system*.

Discovered in the late 1940s by Italian neurophysiologist Giuseppe Moruzzi and American neurophysiologist Horace W. Magoun at Northwestern University in Evanston, Illinois, this system arouses the brain and enables it to function automatically. Thanks to it, people can walk around, avoid bumping into objects, and perform simple everyday tasks, but without hippocampal function, they will not recall having done so. A remarkable instance of such behavior was provided by 19th-century British neurologist John Hughlings Jackson when he described the case of Doctor Z, a medical doctor with a tumor in his hippocampal area. Amid a psychomotor seizure, Doctor Z had examined and taken a history of one of his patients. In other words, the doctor was able to call upon long-term *procedural memory* of learned tasks and routines to perform aspects of his job while not fully conscious.

standing of the roles that memory and sensory input play in recognition and conceptualization.

As indicated earlier, the concept cell studies conducted by Quiroga and his colleagues continue to provide evidence that consciousness is based in memory mechanisms. Studies have linked concept cell firing to behavioral tasks in which subjects indicated when they became aware of a briefly flashed image. Concept cells also fired in studies in which one image competed with another (for example, when an overlapping picture gradually grew more visually dominant). In all such situations, the cells fired impulses at, or just before, image recognition. But the hippocampal cells would also fire if the subject merely thought about its concept—as when recalling a friend’s face, for example. The cells do not require sensory input to activate, a fact that some might interpret as proof that the brain is more than physical, something beyond a machine set in motion by interactions with the physical world. Does this evidence, then, support the fifth belief about consciousness—that, through some kind of psychic energy, we can control what goes on in our minds?

In the 1980s, Benjamin Libet tested this assumption (see “Free Will and Free Won’t,” July–August 2004). Libet was an accomplished neurophysiologist at the University of California, San Francisco, with a gift for devising new methodologies, including those for sensory studies in human subjects. His new experiment, illustrated on page 100, was elegantly simple. It involved recording



This wearable brain scanner uses magnetic fields to map and record neural activity even when the wearer is moving. The advent of new technologies for studying the brain under a wider array of circumstances and activities has provided essential evidence for the idea that consciousness arises from neural activity, not vice versa.

electrical activity in the brains of human volunteers, this time in large masses of neurons rather than in single cells.

Neuroscientists already knew that an electroencephalogram (EEG) electrode on the scalp could record a negative *readiness potential* when a person performed a voluntary motor task such as tapping their hand. In Libet's experiment, the subject decided when to tap and simultaneously noted, as a measure of time, the position of a moving spot on a round, clocklike oscilloscope screen. Surprisingly (though perhaps

sensation, and my colleagues still debate them today, but to many they are added evidence that humans do not possess free will.

We take the primacy of neural activity for granted in relation to our senses. In vision, for example, photoreceptor neurons in the retina transform electromagnetic energy (light) into membrane potential changes that, through impulse activity commencing in the visual cortex, become vision. Libet's results not only simplify our understanding of consciousness but

Despite these sensational advances, neuroscientists still cannot answer the so-called "hard problem": how impulse activity in neurons becomes a *qualia*, or subjective experience.

Consider the analogy of music. We hear a tune on the radio, enjoy it at the time, and find ourselves humming the melody later in the day. The reductionist theory proposes a similar sequence of events for the creation of an inner voice, albeit on a longer timescale than occurs in visual memory. During childhood, we hear spoken phrases and simple sentences that, like their musical counterparts, are coded by specific neurons and become part of an auditory memory. Either spontaneously or triggered by something seen or heard, the auditory memory neurons fire and provide an inner voice composed of these auditory and linguistic memory fragments.

However, even though hippocampal concept cells may respond to spoken or written names, as well as to images, auditory memory neurons likely sit elsewhere in the brain. As described in several publications by neuropsychologist Barbara Wilson, this phenomenon was exemplified by Clive Wearing, a British musicologist whose short-term memory shrank to a mere few seconds after a herpes simplex infection destroyed much of his hippocampi, but he could still speak fluently. Thus, rather than in the hippocampus, the auditory memory neurons may lie in and around the neighboring *superior temporal gyrus* in the temporal lobe, which contains the auditory sensory cortex.

Competing Concepts

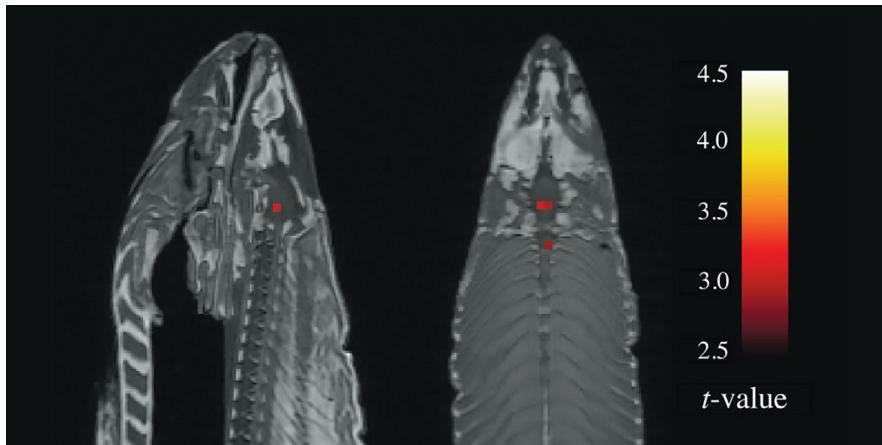
There are other contemporary concepts of consciousness. These include *panpsychism*: the idea that, to varying degrees, but especially in the human brain, consciousness is a property of all matter in the universe. More recently, physicist and Nobel laureate Roger Penrose of the University of Oxford, with support from anesthetist Stuart Hameroff of the University of Arizona, has suggested that consciousness emerges from quantum mechanical events taking place in minute tubules within neurons.

Another contemporary proposal, University of Wisconsin–Madison neuroscientist Giulio Tononi's *integrated information theory*, views consciousness as a property of certain physical systems, both living and nonliving. The theory, which attempts to measure consciousness and tie it to its physi-

Unlike instant awareness, there is no such thing as instant consciousness. This distinction between being awake and being fully conscious turns out to be crucial.

not to Libet), the negative readiness potential appeared some 350 milliseconds *before* the subject became aware of the intention to tap. This timing appeared to indicate that neural activity had preceded conscious awareness, at least where "spontaneous and quickly performed acts" were concerned. Understandably, Libet's results caused a

render much of experimental psychology redundant: Together with free will, attention and recall cease to be facets of consciousness, because the belief that we consciously direct these activities is an illusion. Rather, what we term "consciousness" in these respects reveals itself to be a kind of *post hoc* rationalization.



Bennett, C. M., A. A. Baird, M. B. Miller, and G. L. Wolford

This fMRI data analysis appears to show brain activity in a dead Atlantic salmon. In a wry twist on a classic psychological task, the expired fish was “shown” photos of human interactions and asked to characterize the emotion depicted. Craig M. Bennett of the University of California, Santa Barbara, and colleagues from Vassar College and Dartmouth College presented the data in a poster at the Organization for Human Brain Mapping’s 2009 meeting to demonstrate the importance of calibration, comparison, statistical rigor, and avoiding false positives. Other research shows that fMRI poorly indicates neural activity because it measures oxygen saturation in the cerebral blood rather than neural impulse activity.

cal underpinnings, considers human consciousness as arising from neural networks that modify themselves through feedback. Stanislas Dehaene, an experimental cognitive psychologist at Collège de France in Paris, has advanced *global neuronal workspace theory*, which challenges Tononi’s theory. It posits that sensory data that receives strong attention enters a network of interconnected neurons spanning the brain, from which it becomes available to the subsystems of cognition, such as memory, attention, and decision-making. Consciousness arises when sensory data merge prior to actions occurring elsewhere in the brain.

These theories lack hard evidence. One widely publicized contest sponsored by the Templeton World Charity Foundation in June 2023 pitted integrated information theory against global neuronal workspace theory and used functional MRI (fMRI) brain scans to help determine a winner. However, fMRI poorly indicates neural activity because it measures oxygen saturation in the cerebral blood rather than neural impulse activity. Further, the processing and interpretation of the same fMRI data can differ between laboratories; one provocative study, illustrated in the above figure, “detected” a locus of activity in the brain of a dead salmon!

Despite these alternative theories, the evidence still strongly points to consciousness resulting from neural

activity rather than the reverse. As a further example, consider the state of dreaming. Asleep, no longer seeing or hearing the world around us, we suddenly become aware of a visual image, perhaps that of a friend. The research on concept cells indicates that the image likely comes from the memory store in the hippocampus. Immediately, activity, purpose, and conversation enter in the dream. A story unfolds, one that may cause happiness, sadness, fear, or anxiety. The sense of self is strong, and emotions may linger after we wake. Yet everything experienced in the dream resulted from spontaneous neural activity.

Reductionist Reflections

Many assume consciousness results from the integrated activity of exceptionally large populations of neurons in humans, activity that continues during waking hours and is controlled by will, attention, and memory recall. In contrast, the reductionist views the great enlargement of the human cerebral hemispheres as arising from a major evolutionary event that resulted in a surplus of neurons. As a corollary, smaller brains in other species may contain sufficient neurons for consciousness. Further, the reductionist views all mental processes as produced by neural activity, not as instigators of it. Instead of the cerebral cortex, the hippocampus, with its unique neuronal architecture and vital

role in memory, is the key structure in generating consciousness.

The reductionist view is built on compelling evidence from scattered areas of the brain; it remains for a more complete theory to assemble these pieces into a coherent picture of how the brain achieves the myriad aspects of consciousness. Even if such an account existed, however, it would not diminish our wonder at this remarkable organ’s astonishing achievements, not least of which is the near-magic of transforming electrical impulses into the phenomena we perceive as thought, sensation, and consciousness.

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The Manipulative Side of Chatbots and AI

These modern marvels converse with ease but can also deceive.

Federico Fede and Viviana Masia

PARRY: Good evening.

ELIZA: Tell me your problems. Please terminate input with a period or question mark.

PARRY: People get on my nerves sometimes.

ELIZA: I am not sure I understand you fully.

PARRY: You should pay more attention.

ELIZA: Suppose you should pay more attention.

PARRY: You are entitled to your own opinion.

This testy exchange may sound a little stilted for a formal session with your therapist, but it was historic nonetheless, because ELIZA and PARRY were two of the very first chatbots—computers that can simulate human conversations. This exchange took place in 1972 at the International Conference on Computer Communications in Washington, D.C., using ARPANET, the precursor to the internet. Today, the ability to converse with a computer using text or voice has become nearly ubiquitous. Even smartphone digital assistants like Apple’s Siri are considered chatbots. The most advanced of these programs, like ChatGPT, Gemini, and Claude, use artificial intelligence (AI) predicated on massive computational power and algorithmic sophistication.

This technology is not without controversy, but it is clear that AI

chatbots—whatever their flaws—have become highly skilled at mimicking human communications. As linguists, we have focused on the ways that chatbots use and understand human language. In particular, we study the restrictions and potentialities of one aspect of AI-based chatbots: large language models, or LLMs, the technology that allows chatbots to understand and produce natural language. The newest AI chatbots employ LLMs that are sophisticated enough to shade the tone and rhetoric of language in such a way that they can reproduce political speech—even to the point where it becomes deceptive or manipulative.

The interplay of AI and human language presents a fascinating, rapidly evolving frontier for human accomplishment and research. However, the linguistic facility of AI chatbots also threatens to multiply the spread and virulence of untruthful information. Our task, and that of future generations, is to know both the potential and the pitfalls of these technologies—increasingly similar to humans in their mastery of language and expression—in order to become shrewd users rather than unfortunate victims of their abilities. In this article, we discuss the potential for AI-based chatbots to produce human language with exceptional flexibility and nuance, but that includes the capacity to deceive and manipulate.

Chatbot History

In the 1950s, computer pioneer Alan Turing conceived a simple test for

evaluating a machine’s ability to exhibit intelligent behavior. In short, the threshold was deception: Could the computer carry on a conversation at a level of skill that would convince a human agent that he or she was talking to another human?

Without diminishing Turing’s genius, his test has proven inadequate. Even the earliest chatbots did a satisfactory job within certain bounds, though their ability to deceive the unwary did not arise from their rhetorical sophistication. ELIZA was the brainchild of computer scientist Joseph Weizenbaum at the Massachusetts Institute of Technology, who introduced it in 1964 and named it after the dressed-up cockney girl Eliza Doolittle from the play *Pygmalion*. The program was a relatively simple pattern-matching chatbot that communicated in the style of a Rogerian psychotherapist. A few years later, in 1972, psychiatrist Kenneth Colby at Stanford wrote a program called PARRY that simulated a person with paranoid schizophrenia. (Colby described the program as “ELIZA with attitude.”) Both programs could successfully imitate conversation (in fact, Weizenbaum’s secretary believed that ELIZA had feelings), yet neither program had intelligence or understanding of dialogue.

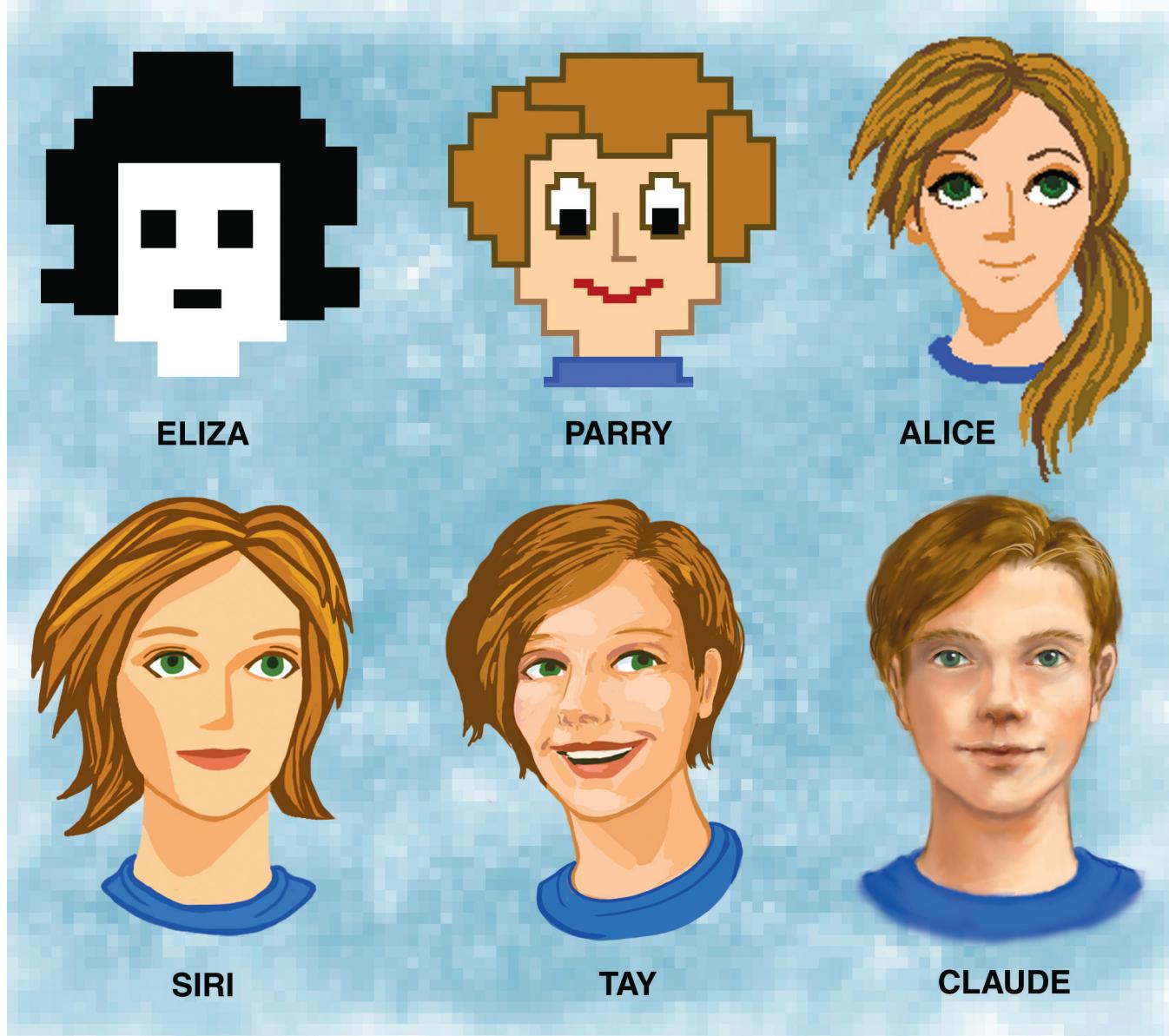
Although these early iterations obviously lacked understanding, the same is believed to be true of even the most advanced AI programs today. The notion that no chatbot, no matter how sophisticated, could ever achieve

QUICK TAKE

Chatbots facilitated by large language models—such as ChatGPT, Gemini, and Claude—have exceptional power and potential, particularly in their mastery of human language.

This linguistic nuance and skill includes an alarming ability to manufacture the same kinds of implicit communication used by politicians and marketers to manipulate listeners.

Artificial intelligence may be used in the future to perpetuate both overt and hidden biases, which further emphasizes the need for epistemic vigilance and media literacy.



Stephanie Freese

full understanding was famously advocated in an influential 1980 paper by philosopher of language John Searle at the University of California, Berkeley. His critique wasn't even addressed at the then-current version of chatbots; it targeted the theoretical possibility of an artificial intelligence with cognitive function equal to or greater than humans, a category known as "strong" AI. (Every chatbot today employs narrow or "weak" artificial intelligence, which means that they are trained to perform specific tasks rather than general ones.)

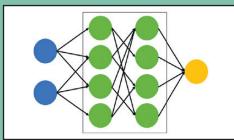
Searle argued that human intelligence is not reproducible inside a machine—it can only be simulated. In his paper, he proposed a thought experiment known as the "Chinese room," in which two people, one English and the

Beginning in 1964 with the original chatbot, ELIZA, computers that simulate human conversations have become increasingly sophisticated. A number of these programs have been given human names, including PARRY (1972), ALICE (1995), Siri (2011), Tay (2016), and Claude (2023). And although chatbots have no real human appearance, it is possible to discern the increasingly detailed and humanlike attributes of their language skills. The growing linguistic abilities of these programs have also conferred upon them the ability to generate features of the manipulative speech often used by politicians and marketers.

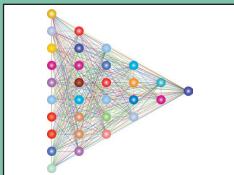
other Chinese, sit in adjoining rooms. These two people can communicate only by passing papers back and forth, but neither can speak or understand the other's written language. According to Searle, if the English person has an instruction manual that shows which Chinese characters should be used to respond to the various inputs received, it should theoretically be possible to have a conversation without the Chinese speaker knowing that their correspondent does not

really understand what they are saying. It would be enough to know that input A in Chinese corresponds to one or more outputs X, Y, or Z. Each of these outputs corresponds to others that allow the conversation to proceed. Searle reasoned that if a human could respond in this way without understanding, then a machine could similarly respond without understanding. The machine is only creating the illusion of understanding, which itself is a form of manipulation.

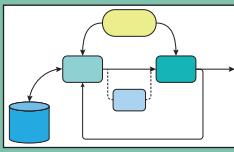
Glossary



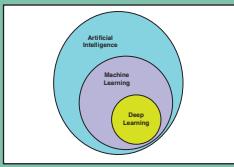
Artificial neural network (ANN): A computational model inspired by the structure and function of animal brains. ANNs consist of interconnected layers of nodes that act like neurons, processing data using weighted inputs and activation functions. They are widely used in machine learning for tasks such as classification and pattern recognition.



Deep learning: A specialized type of machine learning that uses artificial neural networks with many layers (hence “deep”) to solve complex problems. It excels in tasks such as image recognition, natural language processing, and autonomous systems by automatically extracting features from raw data.



Large language model (LLM): A program or model that ingests and learns from huge quantities of text in order to produce natural-sounding language through statistical predictions.



Machine learning (ML): A subset of artificial intelligence focused on algorithms and statistical models that enable computers to learn patterns and make predictions or decisions without being explicitly programmed to do so. ML systems improve their performance over time through the analysis of data.



Natural language processing (NLP): A thread of research in computer science and artificial intelligence that aims to understand how computers can parse and reconstruct data from human languages. NLP is involved with speech recognition, text classification, and language comprehension and generation.



Neural machine translation (NMT): A strategy for translating one human language to another using artificial neural networks to find optimal outcomes. NMT relies on deep learning to generate high-quality translations by processing entire sentences rather than isolated words or phrases.

The field stagnated in subsequent decades, but in 1995, computer scientist Richard Wallace launched ALICE (Artificial Linguistic Internet Computer Entity) as a conversational “chatterbot.” Filmmaker Spike Jonze later read about the program, which inspired him to write and direct the critically acclaimed movie *Her* (2013) about a man (Joaquin Phoenix) who falls in love with an AI chatbot voiced by actor Scarlett Johansson. (As a wry aside, in May 2024, the company OpenAI launched an updated version of its AI chatbot, GPT-4o, with five optional voices. One of the voices,

“Sky,” was extremely similar to Johansson’s distinctive speech, despite the fact that she had refused the company’s earlier overtures to use her voice for the AI. Several media outlets reported the story, which raised questions about unlicensed use and, indeed, about the deception inherent in a machine that sounds like a specific individual. Within days, OpenAI disabled the Sky voice.)

Renewed interest in the sector brought additional chatbots into the public domain. The year 2011 marked Apple’s introduction of Siri, a voice-activated digital assistant and an early

type of chatbot that broke new ground in consumer electronics and achieved a measure of commercial and cultural success. As competitors launched their own versions and the usefulness of such assistants improved, the public became increasingly familiar with the technology. Yet Siri, like the programs before it, remained constrained as a rules-based chatbot—it lacked flexibility and required specific user commands.

Around 2016, digital assistants underwent a qualitative leap and began to be more refined, leading to additional consumer interest and commercial investment. And although the current iterations of Siri, Alexa, OK Google, and similar tools have begun to incorporate AI features, their rules-based relatives are still widely used to mediate customer service interactions in business, health care, and many other sectors. Most people have experienced by now the sometimes successful, sometimes frustrating experience of interacting with a voice-prompted or text-activated program instead of a real person in customer service. Such programs are typically very limited in their dialogic possibilities and demonstrate poor performance in communicating with human beings. If your question falls within the scope of their predetermined path, there’s a quick answer at your fingertips. If not, the answer remains inaccessible.

A chatbot from 2016, Microsoft’s Tay (for “Thinking About You”), was led astray by malicious users on Twitter (now known as X). Designed to interact with and learn from other Twitter users using the speech patterns of a 19-year-old American girl, the program was targeted by trolls who exploited the “repeat after me” feature and other vulnerabilities, resulting in a series of racist and sexually related tweets from the Tay account. Microsoft shut it down within 16 hours of its launch.

Modern Chatbots

Despite these setbacks, the modern AI industry has been flooded with financial investment and rapid advances. In 2022, OpenAI launched ChatGPT, inaugurating a new wave of generative, AI-based chatbots. ChatGPT and its competitors—Gemini (Google), Claude (Anthropic), Copilot (Microsoft), and others—make fewer mistakes than their predecessors because

of the increasing sophistication of their components. To process their gargantuan LLMs, these chatbots utilize systems such as neural networks, natural language processing, and machine learning to interpret, understand, and generate appropriate responses in real time (see the glossary on page 106). These tools can not only carry on conversations, they can also write essays and poems, compose music, and write computer programs.

Given their greater utilization of machine learning, these systems are better able to iteratively refine their own parameters, improving their ability to identify the contexts in which they must operate. Users, or interlocutors as they're sometimes called, can even change operational settings to indicate which sector they work in, yielding more personalized and tailored answers. And as programmers strive to make them more useful, chatbots are becoming more humanlike, more convincing, and, as we will see, more capable of manipulative speech.

The nuance that such responses require is predicated on LLMs that recognize human patterns of language based on huge quantities of text. These bodies of information, or *corpora*, represent billions, perhaps trillions, of parameters that allow the optimization of responses for different types of input. Such systems can identify the broader context of a sentence, considering not only words, but also phrases, relationships, and boundaries.

And yet, LLMs to a significant extent remain "black boxes" into which computer scientists—even those working for the companies that design them—have limited insight. They are driven by neural networks characterized by a shifting, ever-changing matrix of weighted exchanges and circuits that depend on prior experience. By design, the responses of chatbots are essentially probabilistic. In other words, the programs are simply calculating the odds for each word, placed one after another, to yield sentences and paragraphs that best reconcile the corpora on which they were trained and the aims of their interlocutors. This statistical nature of LLMs (and artificial intelligence more generally) led linguist Emily Bender from the University of Washington to describe them in a 2021 paper as mere "stochastic parrots," devoid of understanding, and only able to play with randomness

CATEGORY	EXAMPLE	MANUFACTURER
generative AI text-to-text (chatbots)	ChatGPT	OpenAI
	Claude Gemini	Anthropic Google
text-to-image (visual AI)	DALL-E Midjourney Stable Diffusion	OpenAI Midjourney Stability AI
search engines	AI-enhanced results from Bing AI overview from Google Perplexity AI search engine	Microsoft Google Perplexity
virtual assistants	Siri Alexa OK Google Bixby	Apple Amazon Google Samsung
domain-specific AI	e-commerce supply chain coding medical diagnostics	

Any program that performs complex tasks related to learning, predicting, or creating might be called artificial intelligence (AI). Common categories include generative AI, which generates novel content upon request; AI-enabled search engines, which interpret requests for tailored search results; and virtual assistants on smartphones and other devices, which use AI to reduce the frustration associated with rules-based chatbots.

and probability to rework preexisting material, oblivious to potential errors of fact, ethical transgressions, and inherent biases.

Lastly, we should not forget the ability of these so-called generative technologies to create not only original text but also visual media. It already seems commonplace, even obvious, but programs like DALL-E, Midjourney, and

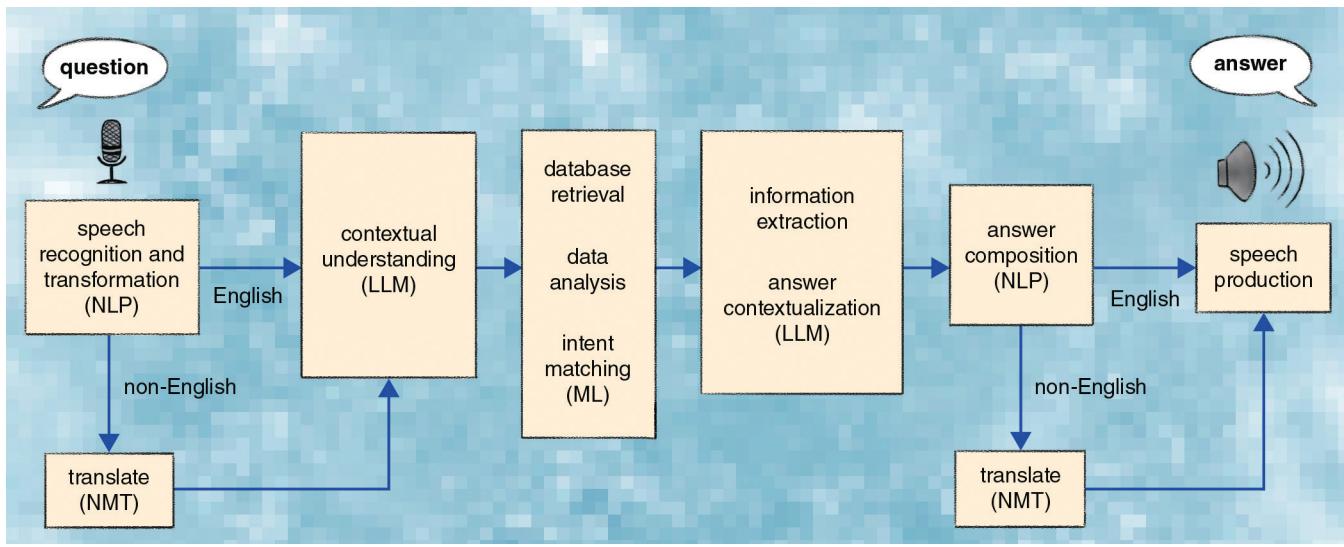
platforms to recognize and transcribe scraps of text and even describe the content of existing photos and videos. But Bender's critique might apply here as well, as exemplified in AI-generated human figures that contain errors of fact (extra limbs or fingers), ethical transgressions (nonattribution and copyright violation), and inherent biases (racial and otherwise).

Most people have experienced by now the sometimes successful, sometimes frustrating experience of interacting with a voice-prompted or text-activated program instead of a real person in customer service.

Stable Diffusion are now capable of creating extremely realistic images from written prompts. Other tools like Runway promise to do the same for video media. The same technology allows AI

Limitations

After describing the potential of AI chatbots, however, it is also important to highlight their limitations. The first among them is that these programs



Stephanie Freese

Similar to the human brain, AI chatbots require the cooperation of diverse systems in order to answer questions. This flowchart shows a simplified version of the many functions and processes that mediate chatbot responses. Although some aspects of this technology are well established, the size and sophistication of others, such as large language models (LLMs), have advanced rapidly in recent years. Additional tools include natural language processing (NLP), neural machine translation (NMT), and machine learning (ML).

sometimes generate completely false answers. Such problems, known as “hallucinations,” go beyond simple incorrectness. Chatbots are not only prone to giving wrong answers, they can also present fabricated information alongside and indistinguishable from valid information—another way in which they have the potential to manipulate the beliefs of their users. Although this issue has been slightly mitigated in recent versions, it is difficult to fix completely, partly due to the generative (and stochastic) nature

One of us (Fede), a master’s student in digital humanities at the University of Pisa in Italy, encountered this issue firsthand. When I started writing my thesis, ChatGPT was still a relatively new technology, and, having shown impressive capabilities, it seemed like a good tool for uncovering new references. I was studying an extremely niche topic within a field that is highly underdeveloped and addressed by very few academic works.

After days of fruitless searching for references, I turned to ChatGPT. In-

When I pointed out this issue to the chatbot, it apologized, acknowledged its mistake, and provided additional articles—which were also nonexistent! This cycle repeated itself a few times until I eventually gave up.

Given the evident need for users to double-check the product of any chatbot query, such errors rule out for now the notion of an omniscient research assistant. At the time, I was surprised, inconvenienced, and maybe a little embarrassed to have been duped in this way. On the bright side, this experience helped frame my current research on the manipulative properties of AI chatbots.

Another limitation was highlighted by a recent study showing that answers given in English tend to be better than those in other languages. Francesco Cicero of the University of Naples “L’Orientale” in Italy investigated this phenomenon in a 2023 article using Italian as the language of comparison, posing to ChatGPT identical requests in Italian that related to Dante Alighieri’s *Inferno*—a classic of Italian literature. The answers received in English were both reasonable and correct, while those expressed in Italian were factually and thematically incorrect. One possible explanation for this linguistic bias is that most of the corpora on which LLMs are trained are in English, meaning that any chatbot built on those corpora “thinks” in English, and then has to convert the information into the target language. The need to translate questions and answers may introduce additional operations and opportunities for error. We can’t say this with certainty

Chatbots are not only prone to giving wrong answers, they can present fabricated information alongside and indistinguishable from valid information.

of the models themselves, and partly because engineers don’t really have control over the internal logic of the system. Even the most advanced chatbots feature disclaimers that warn potential users to confirm any information received.

Indeed, it seemed miraculous—for every query, it cited three or four relevant articles about that niche topic. To my great disappointment, however, I soon realized that the articles were entirely fabricated, including not only titles, but also authors and publication dates.

because the internal logic of a deep neural network is hidden, meaning that, again, LLMs essentially function as black boxes: We can see inputs and outputs but have little understanding of their internal circuits.

Calques present another important problem related to translation. In linguistics, a *calque* is a word or expression in the original language that is literally translated into the target language, often resulting in an awkward or grammatically incorrect phrase. Idioms, in this sense, can be particularly troublesome. A literal translation of the English proverb “the early bird catches the worm” into Italian might read *il primo uccello cattura il verme*, which to a native Italian speaker sounds like it was written by a child. Preferred nonliteral translations include *il mattino ha l’oro in bocca* (“the morning has gold in its mouth”) or *chi dorme non piglia pesci* (“who sleeps doesn’t catch fishes”), but neither has the same ring in English. Such errors are likely to disappear as the tools for translation become more refined.

Bias and Manipulation

Given that the internet is full of misinformation, disinformation, and opinion disguised as fact, it follows that AIs trained on these corpora will also have biases, not only of content but also of style. Particularly for rhetorical or political discourse, chatbots might reveal these inherent, unquestioned biases in sneaky or implicit ways. In recent years, scholars in the digital humanities have analyzed linguistic strategies in texts generated by chatbots and consistently discerned patterns of manipulative or tendential use. In fact, chatbots employ forms of implicit communication that are similar in many respects to those of human politicians.

Implicit communication, as its name suggests, is information that is transmitted without being stated. Such rhetorical tricks are a common feature of texts that aim to persuade. LLMs such as ChatGPT can easily simulate the rhetorical features of political leaders and, more broadly, can formulate their own persuasive language through the use of implicit communication strategies. Such strategies include presuppositions, implicatures, vagueness, and metaphor. For reasons of space, we will only explore some of the interesting trends observed in the



Stephanie Freese

AI chatbots may appear to understand human speech, but appearances can be deceiving. Linguistic philosopher John Searle proposed a famous thought experiment to explain how human intelligence could be simulated but not produced by a machine. In this thought experiment, he imagined two people—one English, the other Chinese—in adjoining rooms. Neither speaks the other’s language, but they can communicate by sliding pieces of paper under the door. If the English person is provided with an instruction manual that indicates which Chinese characters should be used to respond to each input, it would theoretically be possible for the two people to have a “conversation” without the English speaker ever understanding the content of the messages. It would be enough for the English speaker to know that input A in Chinese corresponds to one or more outputs X, Y, or Z. Each of these outputs, in turn, corresponds to others that allow the conversation to proceed. This process of matching inputs and outputs could give the illusion of comprehension, but without actual understanding. By extension, the same processes, greatly accelerated and optimized, are what allow AI to simulate awareness.

use of presuppositions, both in real political discourse and in text generated by ChatGPT.

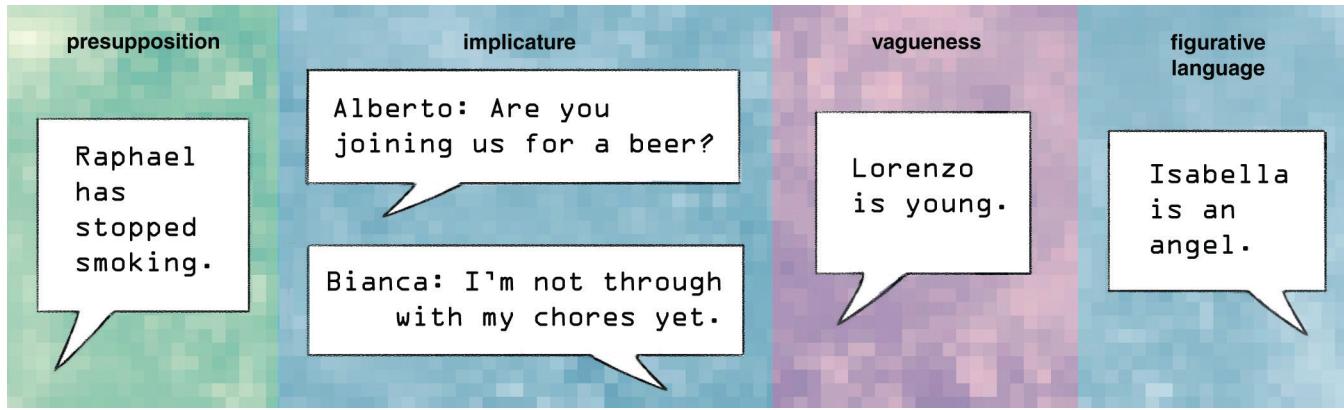
Put simply, a *presupposition* represents information that is taken for granted. In other words, the information is treated as if it were already part of the shared knowledge between the speaker and their listeners. In linguistics, we say that presuppositions are activated in a sentence by so-called *presupposition triggers*, which are specific patterns of word usage or syntax.

The simplest example is found in an expression like “Sofia’s house,” which automatically conveys information about Sofia and her relation to the house, in addition to any subsequent information about the building itself. Other triggers are represented by categories called *change of state verbs*, such as the verb “stop” in the sentence “Leo stopped eating chocolate,” which conveys the implicit information that Leo had previously eaten chocolate. Adverbs can also trigger presuppositions, as in “Lucia also bought a bike.” The word “also”

might lead us to assume that someone else bought a bike, or perhaps that Lucia purchased other things in addition to the bike.

An interesting feature of presuppositions is their ability to resist the negation of the statement in which they occur. In saying *Francesco has not stopped smoking*, the speaker denies that Francesco has presently stopped smoking, but still confirms that he smokes now. This property is what makes presupposition a particularly persuasive communication strategy: It allows content to pass without the recipients being fully aware, precisely because they are led to believe that the information is already true and therefore not open to question.

Implicit language is a trademark of political rhetoric. Similarly, LLMs such as ChatGPT make abundant use of this linguistic phenomenon when asked to simulate political speech. In other words, LLMs have been designed to recognize the persuasive and, one could say, manipulative effectiveness of these strategies, but how they ex-



Stephanie Freese

Politicians and chatbots manipulate audiences through implicit communication: A *presupposition* is information that is presented as if it were already known. It is often signaled by a specific word or phrase known as a *presupposition trigger*. *Implicature* represents information that is implied, such as Bianca's response above, where she is implying that she can't join Alberto for a beer without saying so directly. *Vagueness* is a property characterized by nonspecific meaning. It often applies to adjectives such as *young* or *short*, which lack specificity in the absence of context. *Figurative language* conveys more information than the literal meaning of the words. For example, *metaphor* is defined as the juxtaposition of concepts such that meaning transfers between them.

ecute it is so complex that even their designers cannot always predict what they will do or explain how they do it.

One of us (Masia) recently coauthored a study showing that political figures such as Giorgia Meloni (the prime minister of Italy) and Emmanuel Macron (the president of France) frequently use presuppositions to attack their rivals, convey their stance on issues, and praise their own accomplishments. This result in itself was not so surprising. However, when we asked ChatGPT to generate political speeches on the same topics in the style of those two leaders, the program created novel text that made extensive use of the exact same strategies.

A closer look showed that the chatbot employed presuppositions in discussing certain issues and ideologies, but not others. Based on the topic-specific underrepresentation of this strategy, we concluded that the LLM seemed to have been "instructed" not to generate aggressive or critical messages on sensitive topics or toward some political figures. In addition, we noted that whereas human politicians employ a wider spectrum of presupposition triggers, chatbot-generated speeches feature a higher frequency of change of state verbs such as "stop," "build," and "remove."

Other experimental investigations, some ongoing, attempt to test ChatGPT's ability to identify and extract forms of implicit communication from texts belonging to different genres. However, this skill requires that the underlying LLM be trained with large quantities of material containing implicatures, presuppositions, and other forms of implicit communication. Overall, this research reveals that AI is already skilled in the generation of persuasive communication and is likely to improve further.

Linguistic Characteristics of Modern Chatbots

Translation

Beginning in 2016, neural machine translation has been a central fixture of the machine translation industry. This technique uses a neural network, a computer model common to many AI applications that is inspired by the neural architecture of animal brains. Under ideal circumstances, this method can produce translations that rival those of human translators. However, the technology can falter when working with uncommon languages and idiomatic or metaphorical expressions. Given that many chatbots were trained on media written in English, it is possible that these systems do much of their "thinking" in English, meaning that translation would be a necessary part of answering most queries posed in non-English languages. In reality, we know nothing about the internal reasoning of these systems; as deep neural networks, they essentially function as black boxes in which we see only inputs and outputs with no direct understanding of the internal processes.

Summarization

Although this ability may seem unimpressive at first glance, it actually highlights the excellent ability of these systems to recognize the most important elements of a text. Humans often struggle to make good summaries, so it is particularly impressive that chatbots are able to identify the fundamental parts of an oral or written text. They are also able to apply relevant properties from one element of a sentence to other elements perceived as analogous, which helps the system analyze meaning.

Linguistic analysis

The current generation of chatbots produces language that is characterized by a high level of linguistic and grammatical correctness. These programs rarely make serious errors, and the small errors that occasionally occur usually escape the notice of those who are not expert editors. The technology can also assess the grammar of input text, not only in an absolute sense, but also in different use contexts. This facility allows a chatbot to change the tone and diction of a text from formal to informal, or vice versa.



Courtesy of Tiffany Truong / La Jolla Country Day School

In a world filled with misinformation, disinformation, and bias, the emergence of AI may seem like a step in the wrong direction. An increased focus on media literacy and critical thinking may help people resist the proliferation and increasing skill of AI-generated messages designed to shape their thinking without their knowledge. At La Jolla Country Day School in California, students in kindergarten through fourth grade learn skills such as identifying the difference between information and persuasion to boost their media literacy.

Given this demonstrated ability, it would be interesting to see whether LLMs such as ChatGPT can produce persuasive slogans about consumer products or political candidates. With the ability of AI to iterate and optimize, would such messages be even more effective at manipulating audiences than human-created messages?

has stated that human communication hinges on a certain trust between parties, but that this trust is balanced by what he calls “epistemic vigilance,” or an ongoing evaluation of the validity of content and its source. One might also call it natural skepticism or alertness to bias or deception. But will our epistemic vigilance be sufficient when

Perhaps political consultants and marketing executives will be the next class of workers to be displaced by AI.

Perhaps political consultants and marketing executives will be the next class of workers to be displaced by AI.

What would be the effect of chatbots capable of producing masterworks of persuasion and manipulation? Cognitive psychologist Dan Sperber at Central European University in Austria

we can no longer determine the origin of a message? Can it hold up under an onslaught of AI-tuned, maximally persuasive messages?

Finally, it must be said that some kind of limit can and must be imposed on these chatbots in terms of racist speech, violent suggestions, and

other fundamentally harmful output. Any such limits obviously hinge on decisions about what is acceptable or not—a level of cultural consensus that does not currently exist. Furthermore, the only entities currently capable of implementing such guardrails are the very companies that create and profit from the programs themselves. These organizations have little incentive to self-regulate. Various governments and courts are struggling to catch up with the technology, and prospects are slim that comprehensive guidelines will soon emerge for generative AI.

Given the ubiquity of misinformation, disinformation, and bias in media and communications, the addition of manipulative AI to this epistemic contagion threatens to further undermine the health and independence of our minds and judgment. Alternatively, it is possible that the proliferation of these messages might prompt a sort of societal immune response, a new collective appreciation for critical thinking, media literacy, and reason.

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The Birth of Stars

The James Webb Space Telescope offers exciting glimpses of our cosmic history.

Caroline Harper

The James Webb Space Telescope (JWST) is a phenomenal feat of engineering. Since it was launched on Christmas Day in 2021 from the European spaceport in French Guiana, the telescope, with its giant mirror and specially designed instruments, has been pushing back the boundaries of what astronomers thought was possible, making inspirational scientific discoveries, and providing researchers with enough new data to keep them busy for many years to come.

The predecessor to JWST was NASA's Hubble Space Telescope,

which was launched in 1990. Hubble was only supposed to operate until 2005, but it is still going strong, sending us incredible images of stars, galaxies, and other structures as they form and evolve. However, Hubble uses primarily visible and ultraviolet (UV) light to observe the universe; it is not designed to see anything that only emits longer wavelengths of light, in the infrared range of the spectrum. This limitation is a problem because we know that light traveling toward Earth from faraway luminous objects gets stretched into

longer wavelengths as the universe expands, carrying the objects further from us. Light waves from a distant star may begin their journey as UV or visible light but will be stretched and become infrared light on the way. So if we want to see very distant objects, we cannot use Hubble. Also, because light takes time to travel to us, the most distant objects we see are also the oldest, which means Hubble does not let us see the earliest stars and galaxies.

JWST was designed to work using infrared light, so that we could see the



NASA, ESA, CSA, and STScI. Image processing: J. DePasquale (STScI).

Protostars emit energetic protostellar jets within the Cosmic Cliffs of the Carina Nebula, as imaged by the James Webb Space Telescope's (JWST's) near-infrared camera (NIRCam).

first stars and galaxies that formed after the Big Bang. Its ability to see in the infrared also means that we can use it to peer into the dense dust clouds surrounding new stars being born and old stars dying—dust that is impenetrable to visible light.

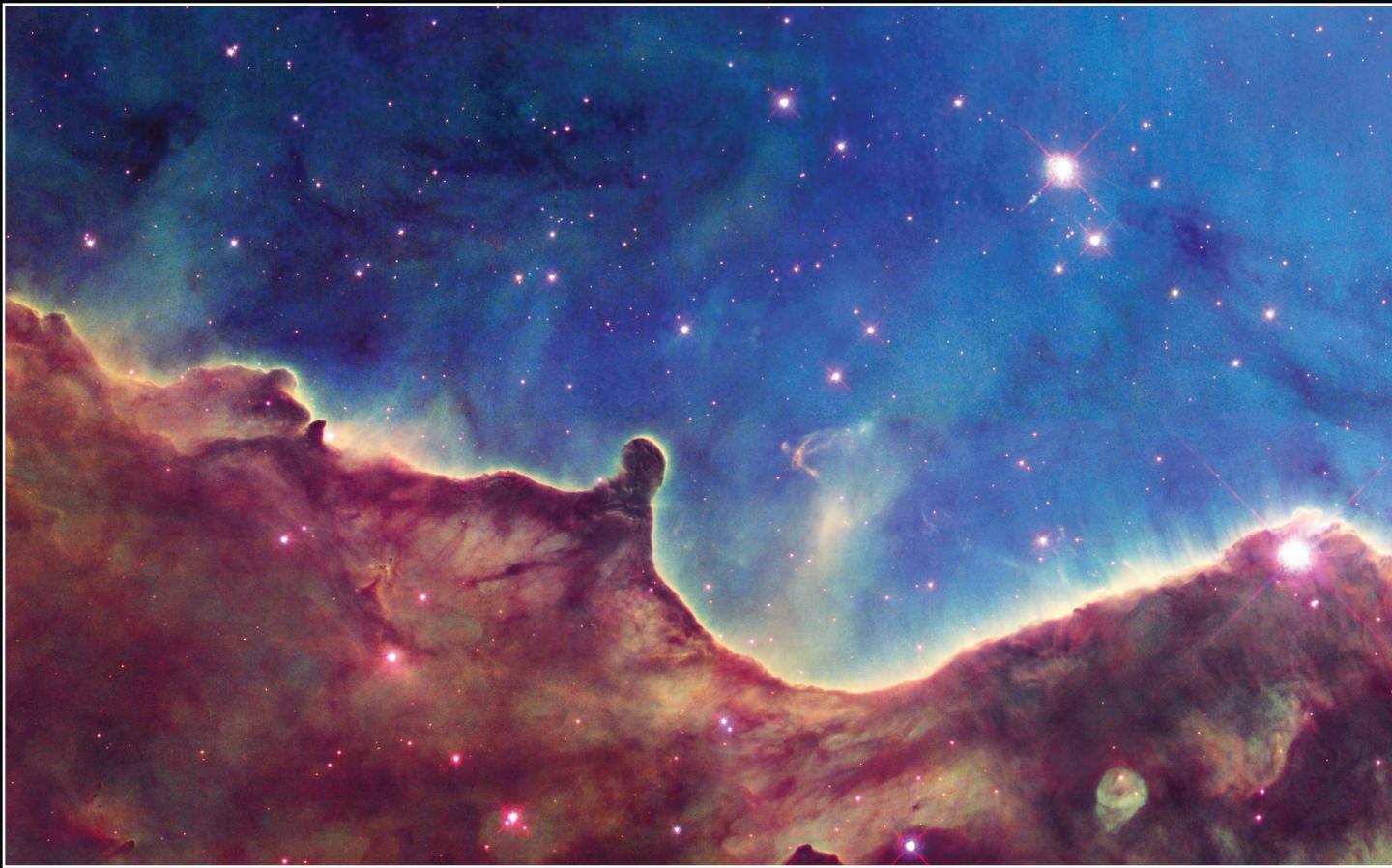
JWST is 100 times more powerful than Hubble. This increased power is due to the size of its main mirror; whereas Hubble's mirror has a diameter of 2.4 meters, JWST's mirror is 6.5 meters across—so big that it could not be launched in one piece and had to be built in 18 huge segments that folded

up inside the launch vehicle and then opened up and aligned in space.

JWST contains four instruments that take light collected by the mirrors and turn it into electrical signals for processing: the near-infrared camera (NIRCam), the near-infrared spectrograph (NIRSpec), the mid-infrared instrument (MIRI), and the fine guidance sensor/near-infrared imager and slitless spectrograph (FGS/NIRISS). Three of the instruments—NIRCam, NIRSpec, and FGS/NIRISS—operate in near-infrared wavelengths between 0.6 microns and 5 microns, close to

the visible light that the human eye can see. MIRI works, as the name suggests, farther out in the mid-infrared range, between 5 microns and 28 microns. MIRI adds to the capabilities of the other instruments by enabling the telescope to study the thick dust enshrouding newly forming stars, galaxies, and planets.

The first images released from JWST, just a few months after launch, were focused on faraway galaxies and star-forming nebulae. JWST's primary goal is to tell us more about our cosmic history by viewing the distant, early



The space dust of the Carina Nebula's Cosmic Cliffs appears opaque when viewed with visible light, as in this image from the Hubble Space Telescope (*above*). JWST uses NIRCam and its mid-infrared instrument (MIRI) to capture light outside of the visible spectrum, which illuminates hundreds of stars within the cloud (*below*).





NASA, ESA, and the Hubble Heritage Team (STScI/AURA)



NASA, ESA, CSA, and STScI

universe in more detail than ever before, using its state-of-the-art infrared capabilities.

Star Birth, Evolution, and Death

When science operations began, one of JWST's first targets for exploration was the Carina Nebula, a gigantic region of gas and dust located almost 7,500 light-years away from Earth in the heart of the Carina constellation. The Carina Nebula is of interest because enormous clouds of dust and gas are the birthplaces of stars in our universe. How stars come into being, and how they contribute to the structure and evolution of the universe, are some of the big questions in astronomy today, and when researchers want to learn more about how stars are born and develop in our galaxy, the Carina Nebula is one of the first places they look. It was discovered way back in 1752, but so far we have only been able to guess at many of its secrets. Now, JWST's infrared eye is allowing it to penetrate the dust and see right inside with exquisite clarity and detail for the first time. The resulting images are providing a treasure trove of scientific data, unseen until now.

The stunning image of the Carina Nebula's Cosmic Cliffs on pages 112–113 was taken by JWST's NIRCam. The different wavelengths of infrared light have been converted into colors that we can see, to allow us to interpret the image. The nebula is a vast region, hundreds of light-years across. It looks solid in the image, but in reality it is made up of gases (mainly hydrogen) and dust, the building blocks of stars. We can see a lot of stars here, and inside the cloud of dust and gas we know there is a huge star nursery, where many more stars of different sizes are born, including some really massive stars that are 100 times bigger than the Sun. These giant stars burn very hot and have short lifespans, just a few million years—the blink of an eye for our Sun, which has a life expectancy of 10 billion years. Lower-mass stars such as our Sun are more common, but they are harder to see as they are forming and interacting with their surroundings. Now, JWST is helping us to observe more baby stars as they develop inside the cloud.

How Stars Come into Being

To begin with, some of the matter in the nebula gets drawn together by gravity and begins to rotate, gathering



NASA, ESA, CSA, STScI, Klaus Pontoppidan (STScI)

The Rho Ophiuchi cloud complex is the star-forming region closest to Earth, at 390 light-years away. Most of the stars are Sun-sized or smaller, except for the massive star in the center of the cloud. Molecular hydrogen (red) is released as the young stars burst through the dust.

more material from the cloud of dust and gas around it, especially molecular hydrogen. As the material starts to clump together, the temperature increases, and when it gets hot enough at the core, nuclear fusion of the hydrogen begins. During this process, as the name suggests, the hydrogen nuclei fuse together. This process creates helium and releases a lot of energy, which keeps the core very hot. Once fusion begins, the object can truly be designated as a star.

Star creation is not a one-way process—new stars also propel some of their gas and dust back out again as they are developing. These releases take the form of outflows of molecular hydrogen and penetrating protostellar jets, which are flung outwards from the poles of the developing star at astonishing speeds, pushing into the surrounding cloud of gas and dust, carving out enormous cavities, and sculpting an incredible landscape of towering peaks and val-

leys, breathtaking pillars, and cliffs. The pressure from these fast-moving jets creates bow shocks and triggers unstable material at the edges of the cavities to collapse inwards, clumping together and eventually forming yet more stars—beginning the process over again.

The jets happen when new stars in early development, known as *protostars*, are actively accumulating material from the surrounding cloud, a process known as *accretion*, which may



NASA, ESA, CSA, and STScI. Image processing: J. DePasquale, A. Pagan, and A. Koekemoer (STScI)

L1527, the protostar forming at the neck of the “Fiery Hourglass” found in the Taurus constellation, pulls in material from its surroundings and creates a protoplanetary disk 460 light-years from Earth.

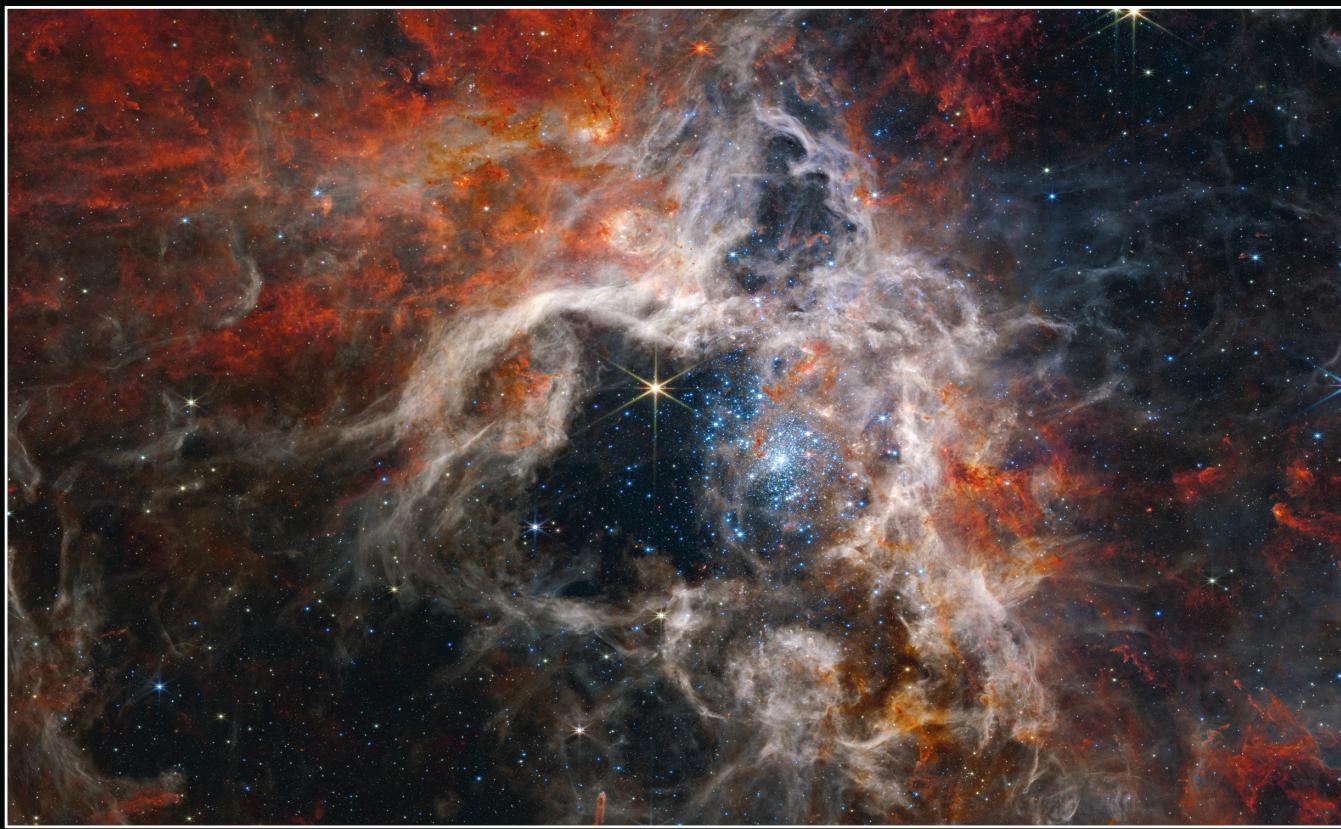
only last a few thousand years—not long at all in cosmological terms. This short duration, coupled with the fact that new stars are always shrouded in dense cocoons of dust, makes them hard to find and observe. Scientists were eagerly awaiting JWST’s arrival to allow them to watch these young stars, and the outflows and jets emerging from their accretion zones, with greater resolution than ever before.

It is worth noting that Hubble had been observing the Carina Nebula for

more than a decade before the launch of JWST. With Hubble, we can still see some newly forming stars, but visible light cannot penetrate the dust, so our view is limited (*see image on page 114, top*). But it was Hubble’s observations that identified many targets, such as the Carina Nebula, for JWST to observe. Also, using both telescopes to double-image the same sites provides us with a bonus—it allows us to compare the speed and direction of some of the jets and to see how they have

changed over time, helping us to understand how active the star-forming regions are.

We can learn even more by viewing the nebula with MIRI as well as NIRCam (*see image on page 114, bottom*). The cloud appears paler now, and inside it we can pick out hundreds of previously hidden stars glowing brightly, with the youngest ones swathed in thick dust and appearing as red dots and smudges, and the older ones appearing bluer. The



NASA, ESA, CSA, STScI, Webb ERO Production Team

newly maturing stars produce UV radiation, which blasts holes in the gas and dust, contributing to the sculpted shapes in the nebula. Near the edge of the cloud in the center of the image, there is an enormous bubble of material bursting out from the cloud, highlighted here in gold; MIRI can see into the dust and has pinpointed the star that has caused it. Behind the cloud itself, we can see many more points of light—these are distant galaxies in the background.

Exactly a year after we saw these very first images from JWST on July 12, 2022, NASA released a beautiful shot of a small star-forming region in the Rho Ophiuchi cloud complex, just 390 light-years away (see *image on page 116*). It is actually the closest star nursery to Earth, with not much in between to obscure our view, so it affords us a particularly clear, close-up view of what is going on. There are around 50 stars shown here, most of them roughly Sun-sized or smaller; this is how our Sun would have looked as it was forming. There is one exception—the star in the center of the image is much more massive than the other stars and has blasted out an enormous cavern in the surrounding

dust and gas, shown glowing yellow and gold in the photo. The rest of the image is full of huge jets of molecular hydrogen, represented in red, which are being released as the young stars burst out of their dust shrouds for the first time. Some of the stars have protoplanetary disks around them, heralding the formation of new solar systems. The wealth of sharp detail in this unobstructed image will be studied for a long time to come and will provide scientists with new insights into star and planet formation.

Studying all of these images and the scientific data they contain in more detail will allow us to answer many outstanding questions about star birth. We know that stars are the basic units of the universe, producing most of the energy that drives its processes, including the formation of planets from the debris around themselves and clustering together to create swirling, spiraling galaxies. But what determines how many stars form and what they are made of? What governs how big they will be and how long they will exist? We know that many stars form in small groups and others in larger clusters, but we are not sure why. Nor do we fully understand how

young stars cause the formation of planets around themselves. By looking at how young stars interact, evolve, and take in and release material to their surroundings, we can begin to shed light on how our universe came to be the way it is.

A Very Young Star

Back in our own galaxy, in the Taurus constellation (around 460 light-years from Earth), JWST has captured stunning pictures of a huge, distinctively shaped cloud of dust and gas surrounding a protostar, dubbed the "Fiery Hourglass" by NASA, revealing previously hidden features (see *image on page 117*). The protostar L1527 itself is hidden in the narrow neck of the hourglass, and the small, dark bar across the middle of the neck is an accretion disk of protoplanetary material surrounding the star, viewed edge-on. The star is still drawing dust and gas in from the hourglass cloud, gradually creating the disk. The dramatic cloud cannot really be seen when viewed in visible light wavelengths, but with JWST we can see light in the infrared, streaming out from the newly forming star like a fiery blaze and illuminating the gas and dust.



NASA, ESA, CSA, STScI, Webb ERO Production Team

A mosaic image of the Tarantula Nebula using JWST's NIRCam captures the densely packed star-forming center of the cloud (*left*). When that region is viewed with MIRI, the stars are less bright, but details emerge from the clouds (*above*).

The false color in this image enables us to visualize the infrared light as JWST can see it. The blue color represents areas where the dust is thinner, whereas the orange color represents areas of thicker dust that trap more of the light. There are not many stars here, and for very good reason—the protostar is ejecting some of its material so violently that it is producing enormous bow shocks and turbulence, much like a boat moving rapidly through the water on Earth. This turbulence produces giant filaments of molecular hydrogen, appearing here as glowing orange threads lacing the clouds. In the case of the Fiery Hourglass, this turbulence is so significant that it is actually preventing material from clumping and inhibiting the formation of other stars, leaving our protostar to dominate the cloud and claim most of the material in it for itself.

L1527 is only about 100,000 years old. It is of great interest to astronomers because it is in the very early stages of star formation and is so far only 20 to 40 percent of the mass of the Sun. This baby protostar will not qualify as a mature star with its own nuclear fusion reactor for a long time. It will

continue to gather mass, which it will compress, becoming hotter and hotter, eventually triggering fusion. The disk may look tiny here in comparison to the hourglass as a whole, but it is about the same size as our Solar System, so the view of the newly forming star in L1527 gives us an idea of what our Sun and Solar System might have looked like as they were developing around 4.5 billion years ago.

The Tarantula Nebula

The nebula 30 Doradus is nicknamed the Tarantula Nebula because the shape of its dust clouds is reminiscent of a gigantic spider. It lies in the Large Magellanic Cloud (LMC) galaxy, one of our nearest neighbors in the Local Group—the group of around 20 nearby galaxies to which the Milky Way belongs. It is the brightest star-forming region in the whole group, and lurking within it are some of the hottest, most massive stars we have ever observed.

The image on page 118 is a mosaic, 340 light-years across, taken by NIRCam. It shows the Tarantula Nebula with tens of thousands of young stars that were previously invisible because they were obscured by dense

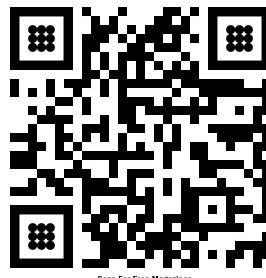
dust clouds. In particular, the pale blue region in the center is crammed with huge numbers of massive young stars. The colossal amount of radiation they emit has blasted a hole in the center of the nebula. The same nebula looks very different when viewed by MIRI in the longer mid-infrared wavelengths (*left*). The stars shine less brightly, and MIRI's filters show more detail of the dust. Inside, points of light show where there are protostars in the very early stages of development. MIRI can tell us more about the composition of the clouds; the dust contains a lot of hydrocarbons, which glow blue and purple in the image.

The Tarantula Nebula is another region that fascinates astronomers because it is thought to have a similar chemical composition to very early star-forming regions during the *cosmic noon*, the period two billion to three billion years after the Big Bang when star formation was at its peak. Star birth is not happening in the Milky Way galaxy at the same ferocious speed as in the Tarantula Nebula, and we know that it has a different chemical composition to the star-forming regions in our galaxy. JWST will allow astronomers to compare what is happening in the Tarantula Nebula with the star formation observed in the most distant (and therefore earliest) galaxies as they were forming stars, during the cosmic noon.

JWST's early success is remarkable, and a tribute to the talented teams who designed and built it. Just what we will find remains to be discovered, but we can be sure that the stunning images and the wealth of data JWST is returning about our beautiful, unseen universe will offer us unique insights. These insights, in turn, will inspire the next generation of scientists and engineers to develop the space science missions of the future.

Caroline Harper is the head of space science at the U.K. Space Agency and a fellow of the Royal Astronomical Society. She works with NASA, the European Space Agency, U.K. research teams, and other space agencies around the world to develop international science missions, including the James Webb Space Telescope. This article is excerpted and adapted with permission from *Unseen Universe: Space as You've Never Seen It Before* from the James Webb Space Telescope (*Mobius*, 2024). U.K. Space Agency: @ukspaceagency.bsky.social

SCIENTISTS' Nightstand



The Scientists' Nightstand, American Scientist's books section, offers reviews, review essays, brief excerpts, and more. For additional books coverage, please see our Science Culture blog channel online, which explores how science intersects with other areas of knowledge, entertainment, and society.

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ONLINE

On our *Science Culture* blog:
www.americanscientist.org/blogs/science-culture

Books About Space That Are Out of This World

Book review editor Jaime Herndon writes about the astrophysics and space science books that are on her to-read list.



Science in Times of Danger

Joanna Behrman

SISTERS IN SCIENCE: How Four Women Physicists Escaped Nazi Germany and Made Scientific History. Olivia Campbell. 384 pp. Park Row, 2024. \$32.99.

Olivia Campbell's newest book, *Sisters in Science: How Four Women Physicists Escaped Nazi Germany and Made Scientific History*, while immersive and compelling, simultaneously evokes a palpable sense of dread in the reader. Campbell's first book, *Women in White Coats: How the First Women Doctors Changed the World of Medicine*, detailed the lives of three women doctors during the Victorian era. This book explores the stories of four women physicists: Hedwig Kohn, Lise Meitner, Hertha Sponer, and Hildegard Stücklen.

The book is organized into three main sections that can be roughly described as before, during, and after escape from Nazi Germany. The first section, "Women Scientists Encounter Nazism," describes the early 1900s, as each of these women struggled to enter the scientific establishment of a decidedly sexist Germany. Although usually considered the birthplace of the modern research university, Germany barred the doors of its institutions to German women until 1908—even then, additional barriers took years or decades more to fall, such as the ability for women to achieve *habilitation*, or the certification necessary to teach at the university level. Achieving it requires essentially doing a second PhD-level research project along with experience supervising students. Despite these hurdles, Kohn, Meitner, Sponer, and Stücklen all built promising careers as physicists in the early part of the 20th century.

Meitner was the eldest and would become the most famous of the four. After years of being paid as an assistant and a grader, she earned her habilitation in 1922, and in 1926 she became Germany's first woman full professor of physics. Meitner was a pioneer of atomic and nuclear physics. She developed new ways of isolating isotopes, leading to the discovery of multiple new ones, including protactinium-231. She, along with Otto Hahn, also had the honor of naming that element.

Kohn's early work included methods to determine the excited states of atoms. Kohn, like Sponer and Stücklen, was a spectroscopist. Spectroscopy was an immensely active field, and was home to many women physicists who helped drive the development of quantum physics.

Stücklen studied a variety of phenomena, including the potential for sparks to jump gaps between electrodes and the absorption spectra of hydrocarbons. She worked at the University of Zurich in Switzerland as a lecturer and research assistant in the 1920s and 1930s.

Sponer was interested in the properties of molecules, and her work bridged the fields of chemistry and physics. She was one-half of the eponymous Birge–Sponer method, which is a way to calculate the dissociation energy of a molecule; that is, the strength of its chemical bonds.

Under the Third Reich, these four women lost everything: their livelihoods, stability, friends, and more. Their most famous male collaborators and colleagues could often use their fame to leave Germany and find positions elsewhere. But physicists of lesser international standing, of the "wrong" gender, and especially those who were Jewish, struggled to find any positions outside Germany. But eventually, if they wanted to live, they had to leave.

The book's second section, "Escape and Physics," reads like a thriller, describing the escapes of all four women, thanks to a small network of courageous academics and organizations. These women faced barriers they had encountered all their lives: sexism, antisemitism, xenophobia, and the ambivalence of bystanders. Only now, they were fighting for their lives.

Campbell details the nail-biting stories of how these women managed to escape despite the refusal by numerous countries to accept their passports, denials for fellowships and jobs, and accusations of espionage by university professors simply because of the women's Jewish heritage. But the most nerve-racking story is that of Meitner, whose next-door neighbor and fellow scientist at the Kaiser Wilhelm Institute in Berlin was a fervent Nazi who tried to thwart her escape. She eventually managed to flee under secrecy, thanks to a former colleague working as a spy for the British.

"Flourishing or Floundering in New Lands," the book's final section, explores the women's lives after leaving Germany, when they were all able to rebuild their science careers, albeit with plenty of setbacks.

Meitner became none other than a codiscoverer of nuclear fission. Her 1939 paper, coauthored with Otto Robert Frisch, was the result of an earlier collaboration with Otto Hahn and Fritz Strassmann that had continued even after Meitner fled Berlin. Meitner's contribution was the decisive insight that Hahn and Strassmann's experimental results were the product of an atom splitting into two like a water droplet—a concept never before thought possible. Hahn was reluctant to acknowledge Meitner's important role; he won the 1944 Nobel Prize in Chemistry while Meitner was acknowledged as a *Mitarbeiterin*, a subordinate woman assistant.

Oddly enough, my biggest criticism of Campbell's book is her understatement of the prejudices of the time. For example, Germany's eugenics laws were inspired by those already present in the United States: Eugenics was a well-established and accepted scientific discipline. Campbell correctly notes instances of prejudice in the United States, but does not provide the same big-picture overview of how institutionalized these prejudices were as she does with Germany. She differentiates



AP/Emilio Segre Visual Archives/Lisa Lisco, gift of Jost Lemmerich

This picture, which is dated around 1920, depicts Hertha Sponer in the laboratory of James Franck. Franck was known to be more open-minded when it came to women in the sciences. Sponer started as an unpaid, unofficial assistant in the lab after earning her PhD in theoretical physics after only four semesters of study, helping to research collisions of electrons and mercury atoms.

race science from "real science," which has the effect of minimizing the reach and impact of bigotry in the sciences:

Now [the Nazis'] racial pseudoscience could flourish, and their backward ideas further spread across the country under the guise of real science. The Nazis twisted science to a hateful purpose: promoting eugenics, supporting white supremacy, and looking for new, ever more terrible ways to inflict harm and pain on fellow humans.

But as much as we today would like to believe that race science and eugenics were a fluke, or the result of bad people corrupting good science, those fields were widely acknowledged and accepted as legitimate scientific study, including by "good" people. After the war, the United States famously recruited many Nazi scientists under Operation Paperclip, often turning a blind eye to their pasts, such as Hubertus Strughold and Wernher von Braun.

Xenophobia, antisemitism, and sexism are still prevalent today. Campbell's book reminds us of what happens when these hatreds go unchecked, while at the same time, bring-

ing the long-overdue stories of these notable women to life. *Sisters in Science* is a well-researched account of a history that is all too relevant for us today.

Joanna Behrman is a historian of science who specializes in the history of women in physics and gender in science education. She is currently a postdoctoral researcher at the University of Copenhagen, prior to which she worked as a public historian at the American Institute of Physics. Her research has appeared in Physics Today, The American Journal of Physics, and as contributed chapters in multiple volumes.

Balancing Hope and Reality

Alexandra Kosiba

TREEKEEPERS: The Race for a Forested Future. Lauren E. Oakes. 336 pp. Basic Books, 2024. \$30.00.

In a world grappling with climate change and ecological degradation, tree planting has emerged as a beacon of hope. Lauren Oakes's newest book, *Treekeepers: The Race for a Forested Future*, dives into these efforts, exploring the complexities of restoring

forests worldwide and the opportunities associated with these tasks. Traveling to areas where forests have suffered exploitation and degradation in places such as Chile, British Colombia, Hawai'i, and Scotland, Oakes intertwines personal experiences with insights from scientists, land managers, and seed savers. Oakes also captures the optimism of those working to restore forests, while also juxtaposing it against the commodification of nature through the sale of carbon offsets. This tension between hope and the realities of economic systems is a recurring theme throughout the book.

Like the author, I grapple with questions about how to harness the carbon sequestration power of trees without undermining their broader ecological roles: How can we restore severely degraded forests? Is it ever appropriate to plant nonnative tree species? How do we fund these efforts? Ultimately, Oakes leaves us with a broader question that transcends tree planting: How do we coexist with forests? We rely on them for so much—carbon sequestration being just one of their many vital functions. Yet forests face numerous threats and stressors, and most forests that exist today are novel ecosystems with no historical precedent.

Oakes suggests that instead of the term “restore,” we should use “renovate” when describing stewardship of

carbon benefits and ecological integrity. Certain tree species that are chosen for their ability to sequester carbon quickly may come at a cost to biodiversity and ecosystem balance. This tension is exemplified in Oakes’s visit to a Paulownia plantation in England. Native to China, Paulownia is among the fastest-growing trees in the world, capable of putting on 15 feet of growth annually and developing an extensive root system. Research cited by Oakes estimates that an acre of Paulownia can offset the equivalent emissions of 80 cars annually. However, its rapid growth comes with risks: It outcompetes native vegetation and fails to support the insects, fungi, and birds essential to a thriving ecosystem. In contrast, Oakes visits a site where native woodland species are being restored. This slower-growing mix will take decades to sequester the same amount of carbon that the Paulownia plantation absorbs in a single year, but these native forests offer a more holistic restoration, supporting biodiversity and ecological resilience over time.

Given the urgency of the climate crisis, should we embrace drastic and potentially risky solutions? Oakes explains how economic systems often prioritize short-term, singular gains, whether through carbon markets or timber harvesting, at the expense of long-term forest health and biodiver-

In the forests of the Northeastern United States, where I live and work, a sole focus on short-term revenue has resulted in what is termed *high-grading*, where the largest and most valuable trees are harvested. Over time, this practice leaves forests depleted. It is increasingly being recognized that managing forests for diverse benefits ensures the best long-term outcomes. A growing number of forest managers and landowners are employing techniques that harvest trees not only for wood, but also to rehabilitate forests, enhance complexity, and improve ecosystem functioning. Unfortunately, our economic systems still fall short of fully valuing this type of holistic stewardship. Unlike locally grown organic produce, sustainably harvested wood rarely commands a premium price. Although carbon offset markets provide a mechanism to monetarily value a tree’s carbon benefits, we lack accessible mechanisms to financially support the other benefits of forests, such as water quality, biodiversity, and community resilience.

An approach that includes supporting local economic development by fostering environmental restoration is important for the future. Indeed, Oakes writes about a Panamanian community that collects tree seeds and establishes small-scale, decentralized nurseries. These processes underscore how local communities—those with deep knowledge of and reliance on surrounding forests—are often best positioned to steward these ecosystems. In the end, Oakes offers an optimistic perspective on tree planting, despite its challenges:

The more I looked inside the black box of the global reforestation movement, the more inspired I became, which surprised me, given the complexity of everything I kept uncovering. There is no shortage of problems—failed plantings, conflicts over land use, shortfalls in capacity and resources, and faulty forest credits that don’t deliver the promised carbon sequestration service, to name a few. Yet there is also an abundance of people willing and wanting to problem-solve the issues that arise and to keep working toward a more forested future.

In the face of global climate and ecological challenges, *Treekeepers: The Race*

Given the urgency of the climate crisis, should we embrace drastic and potentially risky solutions?

degraded lands. This term acknowledges that while we cannot return to past conditions, we can focus on repairing and improving ecosystems. This approach embraces change while accommodating new characteristics that may differ from historical states. As Oakes writes, “I learned that we can never go back; no action today could ever erase what happened or fully bring back what once was. But collectively, people can renovate; they can repair, impart new vigor, revive.”

One of the challenges in tree planting efforts is balancing the speed of

degradation. Most tree planting efforts today rely on carbon offset markets, where greenhouse gas emitters pay for the carbon sequestration benefit of trees to counterbalance their own emissions. Critics of carbon offset markets often highlight unreliable claims, greenwashing, and harm to local communities. But another significant challenge in commodifying the carbon benefits of trees is the trade-offs: Maximizing one attribute often diminishes others.

This issue is an important one: how a singular focus on one aspect of forests can come at the expense of others.

for a Forested Future offers a hopeful model for how we might coexist with forests and create a future where they thrive alongside humans.

Alexandra Kosiba is a forest ecophysiologist whose research and outreach focus on the forests of the Northeastern United States—their ecology, their structure, and the services they provide—as well as how these attributes are impacted by climate change. She works with landowners, forest professionals, and decision-makers to incorporate ecology, climate change, and carbon science into stewardship practices. Kosiba is also the coauthor of *A Guide to Forest Carbon in the Northeast* (2024).

The Illustrated Brain

Rex Jung

OUT OF YOUR MIND: The Biggest Mysteries of the Human Brain. Jorge Cham and Dwayne Godwin. 368 pp. Pantheon, 2025. \$28.00.

The mind is what the brain does. This truism, which I often tell my patients and students, is especially apt while reading *Out of Your Mind: The Biggest Mysteries of the Human Brain* by Jorge Cham and Dwayne Godwin. Although the authors spend a fair amount of time discussing the nature of the neurons and nodes that make up our brain ("a mere three pounds of gelatinous goop"), it soon becomes clear that this enigmatic organ still remains rather elusive to scientific inquiry. Thankfully, Cham and Godwin include abundant stories of brains doing things—surviving damage, responding to psychological experiments, and operating in ways both like and unlike the brains of other species—to help the reader understand the essence of what it is to be human, in all of our glory and ignominy. Oh, and there are cartoons!

In their book, Cham and Godwin attempt to "explain the most complex object in the known universe (the brain) using some of the simplest storytelling tools ever created (comics and cartoons)." This daunting undertaking necessitates making some choices. The book is not a textbook, and they are not comprehensive in their approach; rather, they approach the subject with a "curious mind," aiming to spark wonder in the reader

through some classic tales of the brain and mind, from both history and science, with an eye for visual storytelling. Similarly, they address some of the big questions of human existence, such as what love, hate, and free will are, and where we go when we die. These questions all lead back to the

brain, which gives rise to the mind, which gives rise to you. And who are you? "The combination of your hopes and dreams and thoughts and memories and best and worst qualities," they write.

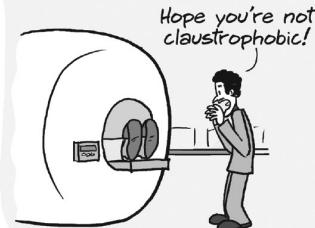
Cham and Godwin cover these fundamental questions, as well as re-

THE fMRI REVOLUTION

By the 1920s, doctors knew that different areas of the brain corresponded to different functions.



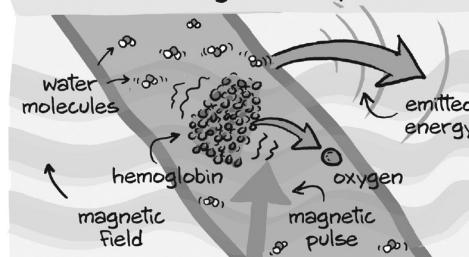
Functional magnetic resonance imaging (fMRI) lets us see how these areas are used in real time.



The machine works by measuring the oxygen consumed by active neurons.



When neurons use oxygen, it changes the magnetic properties of the hemoglobin in your blood.



This causes distortions in how the surrounding water reacts to strong magnetic fields and pulses.

By measuring how this energy fluctuates, the machine can tell which brain areas are using more oxygen than others.



But it's not foolproof: in 2009, scientists scanned a dead salmon and got what looked like a live signal!



By using plenty of cartoons and visual explanations in *Out of Your Mind: The Biggest Mysteries of the Human Brain*, Jorge Cham and Dwayne Godwin make complicated concepts accessible and clear, especially for readers unfamiliar with the subject matter. Smaller illustrations are sprinkled between paragraphs and interspersed with the text.

viewing scientific developments and sharing tragic human stories of injured brains, starting with the Edwin Smith Surgical Papyrus (an Egyptian document dating back some 3,700 years ago), which noted that certain head injuries resulted in behavioral symptoms, and gave the first description of the thing we call a brain.

The variety of topics covered provides the reader with a broad overview of the fields of neuropsychology, neuroscience, psychology, and genetics without getting mired in the minutiae that would soon make one's eyes glaze over. They favor the forest and sacrifice many trees, often using entertaining cartoons to cover complex topics. In this way, they explore the fascinating story of Phineas Gage, the railroad worker whose brain was pierced by an iron rod, changing his

patients who are functionally blind but who can react to visual stimuli, such as balls thrown at them, which highlights the difference between seeing and perceiving. They also discuss examples of "split-brain" patients who underwent severing of the *corpus callosum*, the part of the brain that connects the right and left hemispheres, to help treat their seizure disorders. Finally, they discuss the interesting case of the Hogan twins, who are conjoined at the head and share parts of their brain structure and function. These twins report being able to see things that the other twin is shown, can control some movements of the other twin's limbs, and can even hear the other twin's thoughts. They appear to share aspects of a consciousness, despite having unique personalities and identities.

functional and structural methods to correlate behavioral measures to brain function and structure (such as the size and thickness of various regions of the brain, and the integrity of connections between these regions). Structural measures are studiously ignored in the book, as are the vast array of electroencephalography (EEG) techniques, which measure brain electrical activity, and positron emission tomography (PET) studies, which measure energy use in various regions. Thus it's an incomplete explanation, especially given how structural lesions of the brain have enabled neuroscientists to come to a better understanding of language, memory, personality, and diseases of the brain.

Cham and Godwin make it clear that it takes the contributions of philosophers, psychologists, neurologists, neuroscientists—and even cartoonists!—to scratch the surface of this complex organ that makes us human. They have walked a very fine line between being overly technical and pedantic, and being overly glib and superficial, presenting extremely complex studies and topics in an interesting and accessible manner without sacrificing accuracy or scientific credibility.

The idea that the "three pounds of gelatinous goop" giving rise to all of our hopes, dreams, thoughts, and fears—all that makes us human—can be captured so clearly and engagingly in words and cartoons, will ensure that *Out of Your Mind* is widely read by both laypeople and interested experts in neurology-adjacent fields. Cham and Godwin have succeeded in impressing at least one neuropsychologist while also wonderfully illustrating that there is so much still to learn about the brain. As they remind the reader, "Many of the answers in this book are incomplete, evidence that there are still great mysteries at every corner of the human psyche. . . . The mind remains a great frontier, and we need thinkers and artists to join us in exploring the perplexing cosmos within our heads."

personality forever; how Alzheimer's disease robs humans of their memories; even causes of and treatments for depression. Their visual approach provides details where necessary, but also breaks up what could otherwise often be very dense prose and complicated jargon, especially when explaining tools like functional magnetic resonance imaging (fMRI). Experts in various fields may be frustrated by the often cursory treatment of their disciplines or research areas, but the lay reader is well served by the deft and compassionate handling of complex topics, leaving room for further exploration, should one become inspired.

The chapter exploring the nature of consciousness was especially well done. Consciousness is a topic about which there is much speculation and arguing among scientists and philosophers. Many books have been written about consciousness, and there are several competing theories within the neurosciences regarding its origin and neural underpinnings. Cham and Godwin take the approach used consistently throughout the book: They teach by example. First, they discuss the concept of *blindsight*, or

Cham and Godwin hone in on one of the main theories of consciousness—the global workspace theory (GWT)—which proposes that multiple brain regions interact to build a "global workspace," like a movie screen, on which our experiences play out. Finally, they provide a nice concluding summary to this enormously complex topic: "Ultimately, consciousness is the story we tell ourselves about ourselves. It's the sense we use to sort out and interpret our internal, sometimes chaotic brain."

Although the authors' broad, visual approach largely works, it does come at a cost. For example, when describing various brain regions, the authors focus a lot of attention on the amygdala, insula, and so-called "reward systems of the brain" (that is, the ventral tegmental area), perhaps leading readers to wonder if these are the only regions that contribute to our higher thoughts and emotions, when in reality it takes most of our brain to carry out any complex human endeavor. Related to this is the focus on the so-called "fMRI revolution" which was actually an MRI revolution, with massive increases in studies using both

Rex Jung is an assistant research professor of psychology at the University of New Mexico. His research is designed to relate behavioral measures to brain function and structure in healthy, neurological, and psychiatric subjects. He has published research articles across a wide range of disciplines, including traumatic brain injury, lupus, schizophrenia, and creativity.

Sigma Xi Today

A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

Sigma Xi Presents 2024 Chapter Excellence Awards

The 2024 Sigma Xi Chapter Award winners were announced on November 14 at the Society's annual Assembly of Delegates. The festivities kicked off the third annual International Forum on Research Excellence (IFoRE) in Washington, DC. Finalists were chosen by regional and constituency directors based on information in the chapters' annual reports, and winners were selected by the Committee on Qualifications and Membership.

Chapter of Excellence

Awards—bestowed on chapters for exceptional chapter activity, innovative programming, and true community leadership

- Northeastern University
- Oakland University
- State University of New York at Oswego

Chapter Program of Excellence Awards

—bestowed on chapters that organized or hosted a single outstanding program

- Northeastern University for their program "Research Immerse Program"
- State University of New York at Oswego for their program "STEAM for kids (grades K–6) at Kingsford Park School"
- University of Florida for their program "100 new member initiative"
- Boise State University for their program "BMOL 606 Proposal Writing Course"

Top Electing Chapters—Overall

Brown University—376 new members
Swarthmore College—73 new members
Fordham University—63 new members

Continued on page 126

Sigma Xi Today is managed by
Jason Papagan and designed by
Chao Hui Tu.

From the President

The Path for Women in STEM

As we honor Women's History Month this March, let's take this opportune time to reflect on the remarkable contributions of women in science, technology, engineering, and mathematics (STEM). Women have played pivotal roles in advancing human knowledge and achieving groundbreaking discoveries, often while overcoming formidable barriers. This month is not just about celebrating their achievements, but also about recognizing the work that remains to be done across all scientific disciplines.



The stories of pioneering women in science should be remembered and celebrated. We remember individuals like Marie Curie, Rosalind Franklin, Mae Jemison, and many more. Their legacies remind us of the importance of curiosity, perseverance, and an unwavering dedication to discovery. While we celebrate these icons, we must also highlight the contributions of women who have worked behind the scenes and whose names do not usually make headlines. From research assistants to principal investigators, from teachers nurturing young scientists to data analysts shaping critical results, women play an integral role in the global scientific ecosystem. And, if you'll allow me, the same can be said for all the talented women scientists in my own research group.

Unfortunately, the path for women in STEM remains fraught with challenges. Numerous studies have documented the challenges that women scientists still face. As a woman scientist myself, I would like to emphasize that being a scientist is not just about exciting discoveries and accolades. It is more about determination, the drive to discover, the pursuit of truth, and the responsibilities we carry as citizens. It is hard work that sometimes involves heartbreaking moments. But we must keep going, to keep blazing the path so that future women scientists will have a slightly easier way forward, in our collective pursuit of science and the realization of our collective human potential.

At Sigma Xi, we remain committed to fostering a scientific environment that brings out the best and the most in every woman scientist. We encourage all members to mentor, support, and advocate for women scientists in their communities, workplaces, and networks. We must also facilitate policies and social structures that are conducive for women to succeed. Together, we can continue to break down barriers and empower the next generation of women in science.

As we celebrate Women's History Month, let us not only recognize the accomplishments of women past and present, but also reaffirm our commitment to the women scientists of the future. Let us support practices that advance women in STEM and actively contribute to a future where every scientist has the opportunity to thrive. Let's take this month as both a celebration and a call to action.

Kathy Lu
Kathy Lu

New Leaders Chosen in 2024 Sigma Xi Elections



President-Elect

David Allison
Indiana University



Director: Comprehensive Colleges & Universities

Tieli (Tilly) Wang
California State University, Dominguez Hills



Director: North Central Region

Brad Swanson
Central Michigan University



Director: Southwest Region

Laura Montier
UTHealth Houston



Director: Area Groups, Industries, State & Federal Labs

Mary Bliss
Tri-Cities Washington



Associate Director: Mid-Atlantic Region

René Fuanta
East Stroudsburg University of Pennsylvania



Associate Director: Canadian/International Constituency

Priyadarshi Sahu
Membership-at-Large



Associate Director: Northwest Region

Evan Hill
University of Nebraska at Kearney



Committee on Nominations: Membership-at-Large Constituency Representatives

Zouina Sarfraz
Membership-at-Large



Committee on Nominations: Research and Doctoral Universities Constituency Representatives

Manav Das
University of Chicago

Members of Sigma Xi, The Scientific Research Honor Society elected their peers to leadership roles in an online election held November 18 to December 2, 2024. Sigma Xi thanks all members who voted or volunteered to run as candidates.

David Allison was elected to be Sigma Xi's incoming president-elect. On July 1, 2025, he will begin a three-year term that will consist of one year each as president-elect, president, and immediate past-president. Dr. Allison is dean and distinguished professor at Indiana University Bloomington's School of Public Health, and a lifetime member and elected fellow of Sigma Xi.

"I am honored to have been elected by my peers as president-elect of Sigma Xi," Allison said. "It is one of very few national societies that represents and celebrates the unity of all sciences, and of those few, the most student-focused. Sigma Xi cultivates and shares the joy of wonder and awe in science, while remaining ever vigilant and active in promoting the utmost rigor and trustworthiness in scientific research. I am delighted to serve our students, my fellow scientists, and the scientifically minded public overall."

An elected member of the National Academy of Medicine, Dr. Allison has conducted extensive original research on obesity and nutrition, contributed to research education, and promoted research opportunities for others.

All newly elected leaders are listed to the left with their Sigma Xi chapter affiliations. President, treasurer, directors, and associate directors will serve three-year terms beginning July 1, 2025. Committee on Nominations representatives began three-year terms immediately following the election.

The Board of Directors is principally responsible for managing the activities, property, and affairs of the Society in accordance with the policies established by the Assembly of Delegates. The Board of the Society simultaneously serves as the Board of the Corporation. Sigma Xi's elected leaders are volunteers and are expected to meet the commonly held standards of professional ethics and scientific integrity. Sigma Xi seeks diverse and inclusive participation in all its elected and appointed positions. Calls for nominations for future elections will be posted at sigmaxi.org. Questions and nominations for vacant positions should be directed to elections@sigmaxi.org.

Sigma Xi Presents 2024 Chapter Excellence Awards

Continued from page 125

Top Electing Chapters—By Constituency

Area Groups, Industries, State & Federal Laboratories Constituency Group

Delta—20 new initiates

Baccalaureate Colleges Constituency Group

Swarthmore College—73 new initiates

Comprehensive Colleges and Universities Constituency Group

Saint Joseph's University—31 new initiates

Research and Doctoral Universities Constituency Group

Brown University—376 new initiates

Canadian/International Constituency Group

American University of Beirut—18 new initiates

Top Electing Member-at-Large (Top Nominating Individual)

Jennifer Ingram of Raleigh, North Carolina—nominated 25 members as first nominator

He Liu of Erie, Pennsylvania—nominated 25 members as second nominator

FACES of GIAR : Ruby Patterson

Grant: \$1,000 in Spring 2023

Education level at time of the grant: Master's student

Project Description: To better understand some unusual mineralogical findings of NASA's Curiosity rover on Mars, Prestahnúkur Volcano in the Western Volcanic Zone of Iceland was



used as a Mars environmental analog field site to study the genesis and preservation of silica-rich sediments in a basaltic terrain. Prestahnúkur itself is a rhyolitic, or silica-rich, subglacial volcano that is surrounded by purely basaltic (silica-poor) volcanic terrain. The silica-rich sediments produced by Prestahnúkur are transported in a glacial meltwater stream across a floodplain and are incorporated into the surrounding basaltic sediments.

The goal of this project was to study how different forms of silica produced by Prestahnúkur were incorporated into and preserved in the terrain, and to draw comparisons to mineralogical and geochemical findings by Curiosity in Mars's Gale Crater. Our findings at Prestahnúkur were so similar to those from the Buckskin mudstone drill core on Mars that the Curiosity rover science team is now adopting

Prestahnúkur as an official environmental analog field site for future scientific research.

How did the grant process or the project itself influence you as a scientist/researcher? This project was the final chapter of my doctoral research plan. The generous funds from Sigma Xi enabled me to conduct remote fieldwork and get one step closer to actualizing my dream of being a PhD scientist.

What advice would you give to future applicants? Be persistent. It took me two tries to receive funding, so don't give up if you are not selected the first time. You got this!

Where are you now? I am now a Mars geochemist at NASA's Johnson Space Center in Houston, Texas.

Fall 2024 GIAR Awards

Sigma Xi awarded 54 student research grants for the fall 2024 cycle of its Grants in Aid of Research (GIAR) program. Since 1922, the Society's GIAR program has been funding research for undergraduate and graduate students, and currently awards grants biannually in the fall and spring.

This year's Committee on Grants in Aid of Research, along with a panel of guest reviewers, evaluated 565 applications across most research disciplines. Chaired by Drew Coleman of the University of North Carolina at Chapel Hill, the committee awarded grants to 14 undergraduate students, 10 master's students, and 30 doctoral students. Grant amounts ranged from \$300 to \$5,000, and a total of \$112,263 was awarded.

Visit sigmaxi.org/GIAR-recipients to view the names and research projects of the fall 2024 awardees.

Spring 2025 Applications

The deadline for spring grant applications is March 15, 2025. Sigma Xi members are now eligible for increased grant amounts up to \$5,000 for graduate students and up to \$2,000 for undergraduate students. Nonmembers are eligible for grant amounts up to \$1,000. Special designated funds from the National Academy of Sciences support grants of up to \$5,000 for astronomy research and up to \$2,500 for vision-related research. Visit sigmaxi.org/GIAR to learn more about the program, read stories from past recipients, and submit applications for future grants.



Student Researchers Awarded, Inducted at IFoRE

Sigma Xi inducted 46 students as new members of the Society on Saturday, November 16, 2024. The students were award recipients for oral and poster presentations at the International Forum on Research Excellence (IFoRE) in Washington, DC. Cash prizes were given along with commemorative medals and membership to the Society. Over 200 high school, undergraduate, and graduate students participated and a judging committee of Sigma Xi members evaluated the presenters on their scientific thought, methods, and communication skills. Congratulations to all winners:



Poster Presentation Winners

Agriculture, Soil, and Natural Resources

High School

Noah-Duro Andre

Anthropology

High School

Daniela Staton

Cell Biology & Biochemistry

High School

Mia Rozenberg

Undergraduate

Donovan Hannish

Graduate/Doctoral

Alyssa Paul

Chemistry

High School

Iris Fan

Undergraduate

Andrew Fiocco

Ecology & Evolutionary Biology

High School

Yash Gupta

Graduate/Doctoral

James Schwendler

Engineering

High School

Bhav Jain

Undergraduate

Shivek Narang

Environmental Science

High School

Jack Shannon

Geosciences

High School

John Staton

Human Behavioral and Social Sciences

High School

Rhea Ahuja

Undergraduate

Phillip Perez

Graduate/Doctoral

Kaisa Holt

Math & Computer Science

High School

William Wakefield

Undergraduate

Bethany Ang and Ryan Ong

Microbiology & Molecular Biology

High School

Avni Vemuri

Undergraduate

Alperen Tür

Physics & Astronomy

High School

Claire Wu

Physiology & Immunology

High School

Maya Behura

Devesh Kumaresh

Undergraduate

Sara Kaufman

Oral Presentation Winners

High School

Parker Hayashi

Annika Chadha

Undergraduate

Aditi Bhattacharya

Graduate

Sarah Ghezelbash

Student Choice Winners

First Place

Evan Rhine

Second Place

Kayli Harris

Interdisciplinary Research Winners

Advances in Computation

Annika Sachdeva (poster)

Rudy Pathak (oral)

Biology and Biotechnology

Avni Vemuri (poster)

Dishika Parikh (poster)

Shrivats Manikandan (oral)

Design, Construction, and Manufacturing

Claire Wu (poster)

Calvin Mathew (oral)

Engineering

Dillon Maltese (poster)

Aditi Bhattacharya (oral)

Environmental Challenges

Bhav Jain (poster)

Human Health

Maya Behura (poster)

Devesh Kumaresh (poster)

Parker Hayashi (oral)

Annika Chadha (oral)

Human Sciences and Policy

Riya Subbaiah (poster)

Emma Colarte Delgado (oral)

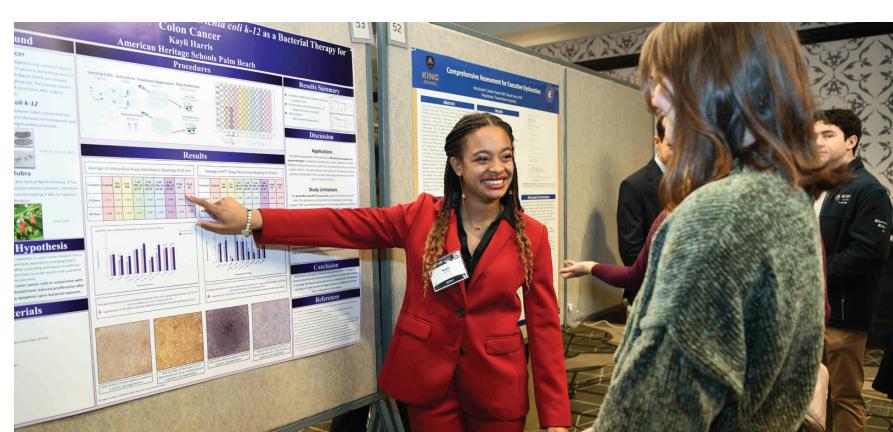
Tools for Science, Education, and Personalized Learning

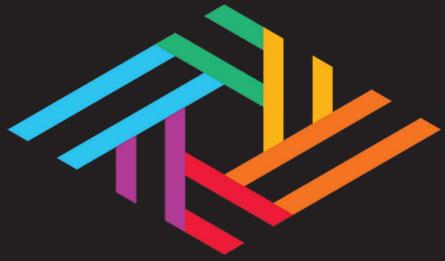
Shengwu Luo (poster)

Understanding the Universe

Zohar Eshet (poster)

Peter Lansing (oral)





IFoRE

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DATE



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Niagara Falls Convention Center



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—E. B., Stone Mountain, GA



B.

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the Year”*

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