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SCIENTIFIC AMERICAN Space & Physics

Galactic Wormholes

DOES THE MOVEMENT OF STARS AT THE CENTER OF THE MILKY WAY REVEAL TUNNELS THROUGH SPACETIME?

Plus:

A QUANTUM-COMPUTING GOLD RUSH

GRAPHENE ELECTRONICS BOOM

WATER ON EXOPLANET 124 LIGHT-YEARS AWAY

WE'RE DUE FOR A GEOMAGNETIC SUPERSTORM

WITH COVERAGE FROM nature

LIZ TORMES

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Wormholes within Reach?

In the 1967 episode of *Star Trek* "The City on the Edge of Forever," the crew of the *Enterprise* finds itself on an alien planet and discovers a large, doughnut-shaped machine referred to as a "time portal" that can transport anyone across spacetime to any time or place in the universe. Though not explicitly called a wormhole, it is one of the earliest appearances of the theorized cosmological phenomenon in popular science fiction. And certainly not the last. The intriguing prospect of traversing hundreds of millions of light-years in an instant is explored by numerous films, from *Thor* to *Interstellar*–not to mention several more episodes of *Star Trek* in all the various iterations of the franchise over many decades. But the existence of wormholes, while hypothesized, has never been proved and remains a controversial topic in physics. As Jonathan O'Callaghan explains in "Hidden Passage: Could We Spy a Traversable Wormhole in the Milky Way's Heart?" a team of researchers now proposes that we might be able to determine the existence of a wormhole by measuring gravitational pulls from stars on the other side of the portal. It's a fascinating premise, and we won't have to wait until stardate 48579.6 to get the results.

In a special report in this issue, we present some of the latest news on quantum technology. Investments are pouring into this research that promises to revolutionize encryption, medical imaging and basic computing, as Elizabeth Gibney writes in "The Quantum Gold Rush," the first article of this series. But will the upfront costs bear fruit? Many physicists are betting that this new wave of technology will live long and prosper. (Sorry, I had to.)

Andrea Gawrylewski
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MARK GARLICK *GETTY IMAGES*

On the Cover

Does the movement of stars at the center of the Milky Way reveal tunnels through spacetime?

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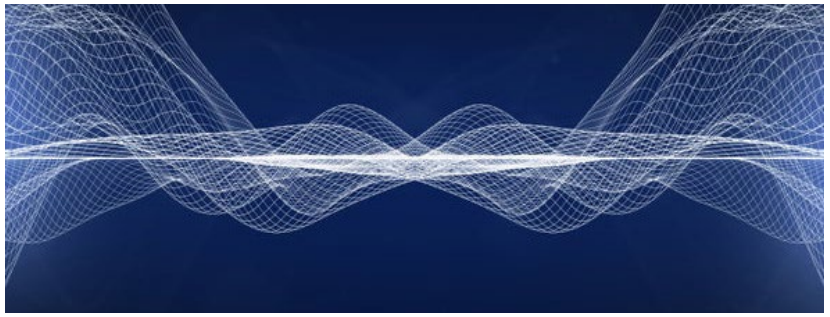

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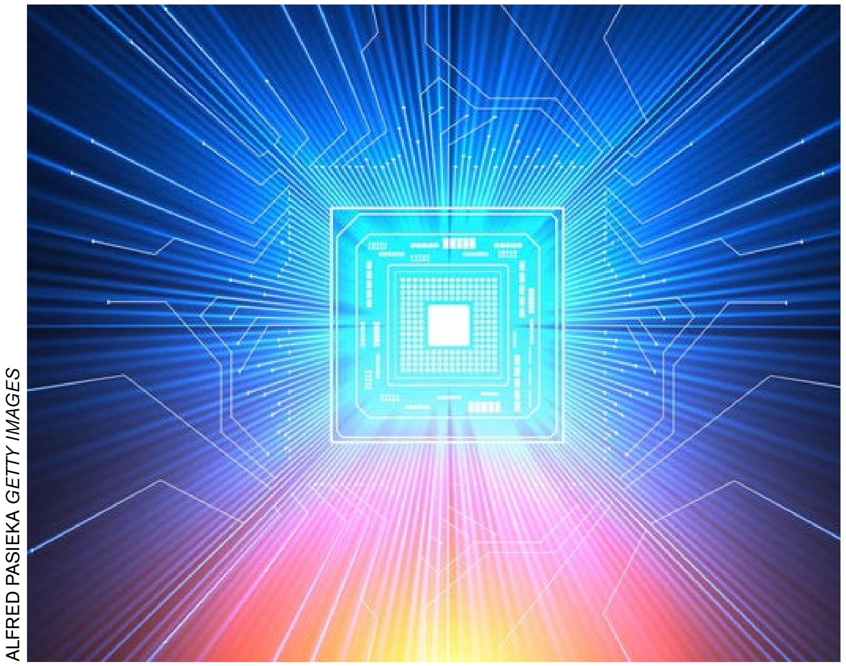

ALFRED PASIEKA *GETTY IMAGES*

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Trapping the Tiniest Sound

Controlling the smallest unit of sound could have applications in quantum information

RESEARCHERS HAVE GAINED control of the elusive “particle” of sound, the phonon. Although phonons—the smallest units of the vibrational energy that makes up sound waves—are not matter, they can be considered particles the way photons are particles of light.

Photons commonly store information in prototype quantum computers, which aim to harness quantum effects to achieve unprecedented processing power. Using sound instead may have advantages, although it would require manipulating phonons on very fine scales.

Until recently, scientists lacked this ability; just detecting an individual phonon destroyed it. Early methods involved converting phonons to electricity in quantum circuits called superconducting qubits. These circuits accept energy in specific amounts; if a phonon’s energy matches, the circuit can absorb it—destroying the phonon but giving an energy reading of its presence.

In a new study, scientists at JILA (a collaboration between the National Institute of Standards and Technology and the University of Colorado Boulder) tuned the energy units of their superconducting qubit so phonons would not be destroyed. Instead the phonons sped up the current in the circuit, thanks to a special material that created an electric field in response to vibrations. Experimenters could then detect how much change in current each phonon caused.

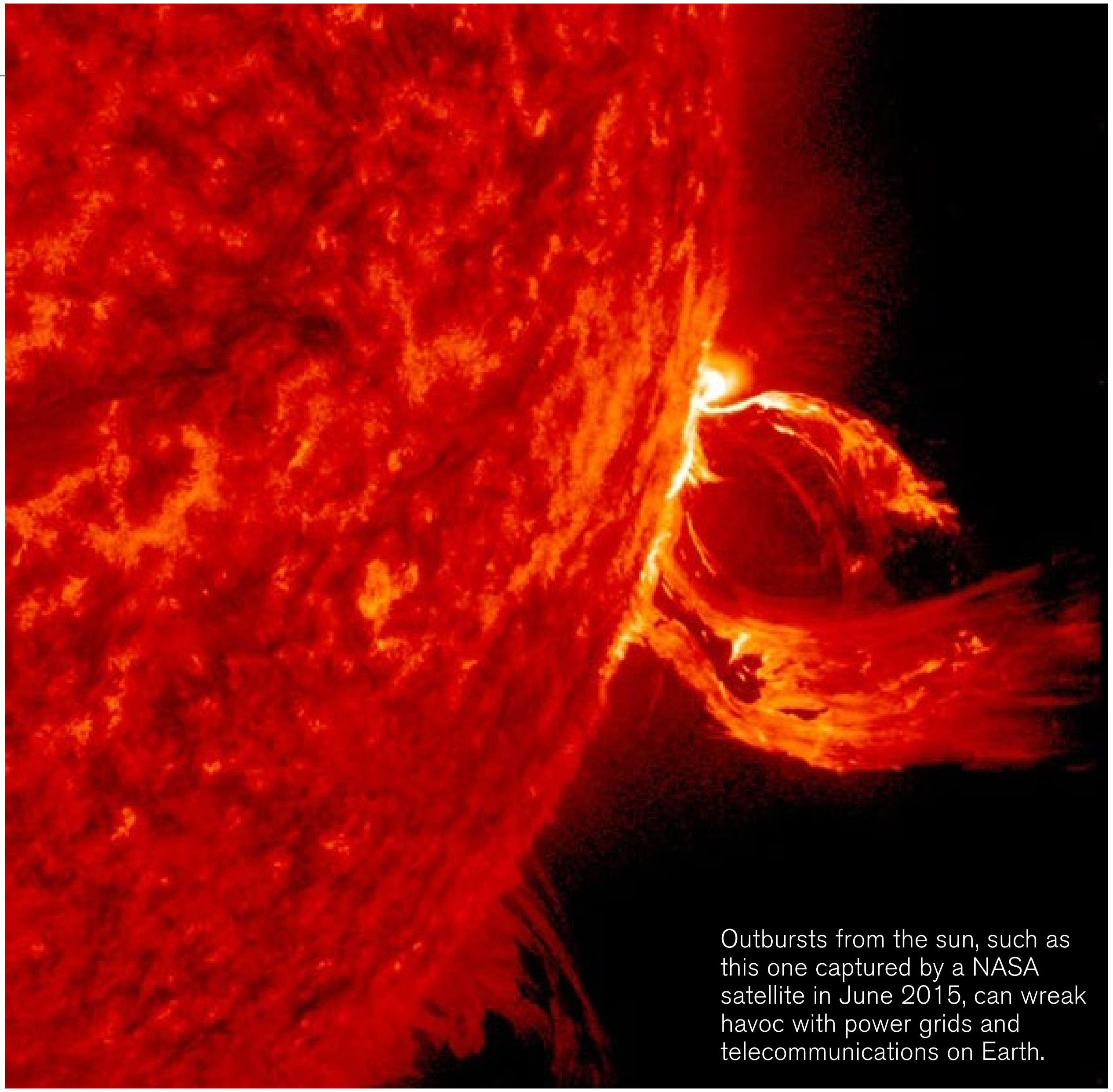
"There's been a lot of recent and impressive successes using superconducting qubits to control the quantum states of light. And we were curious—what can you do with sound that you can't with light?" says Lucas Sletten of U.C. Boulder, lead author of the study published in June in *Physical Review X*. One difference is speed: sound travels much slower than light. Sletten and his colleagues took advantage of this to coordinate circuit-phonon interactions that sped up the current. They trapped phonons of particular wavelengths (called modes) between two acoustic "mirrors," which reflect sound, and the relatively long time sound takes to make a round trip allowed the precise coordination. The mirrors were a hair's width apart—similar control of light would require mirrors separated by about 12 meters.

Sound's "slowness" also let the experimenters identify phonons of more than one mode. Typically, Sletten says, quantum computers increase their capacity through additional superconducting qubits. But having just one qubit process information with multiple modes could achieve the same result.

"This is definitely a milestone," says Yiwen Chu, a physicist at ETH Zurich, who was not involved in the study. Analogous experiments with light were a first step toward much of today's work on quantum computers, she notes.

Similar applications for sound are far off, however: among other things, scientists must find a way to keep phonons alive much longer than they currently can—about 600 nanoseconds. Eventually, though, the research could open new paths forward in quantum computing.

—Leila Sloman



Outbursts from the sun, such as this one captured by a NASA satellite in June 2015, can wreak havoc with power grids and telecommunications on Earth.

SOLAR DYNAMICS OBSERVATORY AND NASA

New Studies Warn of Cataclysmic Solar Superstorms

Data suggest the 1921 New York Railroad Storm could have surpassed the intensity of the famous Carrington Event of 1859

A POWERFUL DISASTER-INDUCING geomagnetic storm is an inevitability in the near future, likely causing blackouts, satellite failures, and more. Unlike other threats to our planet, such as supervolcanoes or asteroids, the time frame for a cataclysmic geomagnetic storm—caused by eruptions from our sun playing havoc with Earth's magnetic field—is comparatively short. It could happen in the next decade—or in the next century. All we know is, based on previous events, our planet will almost definitely be hit relatively soon, probably within 100 years.

Geomagnetic storms are caused by sunspots, solar flares and coronal mass ejections, resulting in calamities to which our modern technological society is becoming ever more susceptible. Most experts regard the Carrington Event, a so-called superstorm that occurred in September 1859, as the most powerful geomagnetic storm on record. But new data suggest that a later storm in May 1921 may have equaled or even eclipsed the Carrington Event in intensity, causing at least three major fires in the U.S., Canada and Sweden—and highlighting the damaging effects these storms can have on Earth today.

In a paper published in the journal *Space Weather*, Jeffrey Love of the U.S. Geological Survey and his colleagues reexamined the intensity of the 1921 event, known as the New York Railroad Storm, in greater detail than ever before. Although different measures of intensity exist, geomagnetic storms are often rated on an index called disturbance storm time (Dst)—a way of gauging global magnetic activity by averaging out values for the strength of Earth's magnetic field measured at multiple locations. Our planet's baseline Dst level is about −20 nanoteslas (nT), with a "superstorm" condition defined as occurring when levels fall below −250 nT. Studies of the very limited magnetic data from the Carrington Event peg its intensity at anywhere from −850 to −1,050 nT. According to Love's study, the 1921 storm, however, came in at about −907 nT. "The 1921 storm could have been more intense than the 1859 storm," Love says. "Prior to our paper, [the 1921 storm] was understood to be intense, but how intense wasn't really clear."

Chris Balch of the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (SWPC), who was not involved in the paper, notes that there are several ways to measure the intensity of geomagnetic storms. Whereas Dst is a good measure of events in the past, he says it is less useful for modern real-time analyses of storm intensity and energy, which instead rely on something called the KP-index. "Dst is based on these low-latitude observatories around the world," he says. "For [the KP-index], there are 13 observatories located in auroral zones and at midlatitudes." Being closer to Earth's geomagnetic poles, these stations are able to get a better handle on fluctuations in the field's strength.

"I was really excited to finally see a quantitative measure of the 1921 event."
—Delores Knipp

Historical measurements of geomagnetic storms are not easy. Whereas today we have an array of instruments around the world to monitor such events, our knowledge before 1957—when official Dst records began—relies on disparate data taken by different magnetometers scattered around the globe. Before Love's paper, data from only one observatory in Samoa had been used to estimate the 1921 storm's intensity. But he was able to track down additional handwritten records from other locations in Australia, Spain and Brazil. Averaging out the readings from these four locations, Love and his co-authors reconstructed the 1921 storm's intensity more accurately than ever before—much more accurately, for instance, than intensity estimates of the Carrington Event, which currently rely on just a single magnetometer measurement from India. "I was really excited to finally see a quantitative measure of the 1921 event," says Delores Knipp of the University of Colorado Boulder, who is an editor at *Space Weather*. "I think it's actually something that will come as a surprise to many people."

The Carrington Event is particularly famous for its effects on Earth, sending geomagnetically induced currents coursing through the planet's nascent electric grid and starting fires worldwide. A new analysis published in *Space Weather* a month before Love's paper, however, shows the effects of the 1921 New York Railroad Storm were just as severe, if not more so. Although the latter event gets its name from disruption to trains in New York City following a fire in a control tower on

May 15, study author Mike Hapgood of Rutherford Appleton Laboratory in England found that the association between those occurrences and the storm was weak. But looking at previously overlooked written records, Hapgood noted that three major fires had erupted on the same day. One, sparked by strong currents in telegraph wires at a railroad station in Brewster, N.Y., burned the station to the ground. The second was a fire that destroyed a telephone exchange in Karlstad, Sweden, and the third occurred in Ontario.

The 1921 event unfolded in two phases, unleashing an opening burst of disruption before intensifying into a full-fledged superstorm. In Karlstad, for instance, night-shift operators of the telephone exchange initially reported that their equipment was malfunctioning and had begun emitting smoke. After the smoke cleared, in the hours before dawn, electrical cables in the exchange erupted in flames, eventually setting the entire structure ablaze. By sunrise, the interior had burned to ashes.

Hapgood's research shows just how impactful the storm of 1921 really was—and not just in the U.S. and Sweden. Records from Samoa, which is not far from the equator, show that auroral displays were visible to observers even in this low-latitude locale. "It's an astonishing observation," Hapgood says. Auroras were also recorded near Paris and in Arizona, at the same time telegraph systems and telephone lines were disrupted in the U.K., New Zealand, Denmark, Japan, Brazil and Canada. "[This storm] has gotten a period of earlier activity that caused some problems," Hapgood says, "and then the next night, all hell broke loose," as what began as a more modest event from the sun grew in strength to become far more disruptive.

Today we have sentinel spacecraft in place, such as NASA's Advanced Composition Explorer, to monitor space weather and provide warnings to Earth if a large storm is heading in our direction. This system should allow power grids or satellites to be shut down as a storm arrives to lessen its effects. But if an exceedingly large storm were to strike again—as one very nearly did in 2012—the results could be severe, regardless of forewarnings. "If the 1921 storm occurred today, there would be widespread interference to multiple technological systems, and it would be quite significant," with effects including blackouts, telecommunications failure and even the loss of some satellites, Love says. "I'm not going to say it would be the end of the world, but I can say with high confidence that there would be widespread disruption."

Whereas another large event would undoubtedly cause problems, organizations such as the SWPC closely monitor space weather to prepare the planet for the worst. Knipp believes that policy makers have now started to pay an "appropriate level of attention" to the issue, but she notes there is only so much that can be done to prepare. And although the Carrington Event has long been the canonical storm for forecasting what might one day come our way, maybe now the New York Railroad Storm and its impacts should be equally revered.

"I think that the 1921 storm is maybe worthy of just as much discussion," Love says. "These two storms are, far and away, the biggest ever recorded."

—Jonathan O'Callaghan

Cosmology and Exoplanets Win 2019 Nobel Prize in Physics

James Peebles, who helped found the field of cosmology, shares the prize with Michel Mayor and Didier Queloz, discoverers of the first exoplanet around another sunlike star

DISCOVERIES ON THE GRANDEST scale in the cosmos, as well as findings a bit closer to home, share this year's Nobel Prize in Physics. Cosmologist James Peebles of Princeton University won half the award for helping to build our picture of how the universe formed and evolved. And the other half went to Michel Mayor of the University of Geneva and Didier Queloz of the University of Cambridge and the University of Geneva for finding 51 Pegasi b, the first exoplanet orbiting a sunlike star.

Together, the winners "have painted a picture of a universe far stranger and more wonderful than we ever could have imagined," said Nobel committee member Ulf Danielsson, a physicist at Uppsala University in

Sweden, at a press conference. “Our view of our place in our universe will never be the same again.”

Peebles helped predict the cosmic microwave background radiation—the first light in the universe, which allows scientists to trace the earliest epochs in the cosmos. Over a half-century career he has shaped our view of how the big bang created matter, how galaxies formed and what makes up the missing bulk of the universe—the unknown entities of dark matter and dark energy. “Isn’t it fascinating,” Peebles said during a Nobel announcement interview, “that we have very clear evidence that our universe did expand from a hot, dense state, but although the theory is very thoroughly tested, we still must admit that the dark matter and dark energy are mysterious?”

The other side of the prize this year honors one of the pioneering discoveries in exoplanet science: the 1995 revelation of 51 Pegasi b. Mayor and Queloz carefully measured a star’s velocity, finding that it wobbles back and forth in a telltale pattern produced by the gravitational pull of an orbiting planet.

Before this finding, the only confirmed exoplanet known orbited a pulsar—a dense remnant from a supernova explosion. The world 51 Pegasi b, on the other hand, orbits a “main sequence” star, the same category as our sun, about 50 light-years from Earth. It was the prototype “hot Jupiter”—a massive gas giant around the size of the solar system’s largest planet (in this case about half the mass of our own Jupiter) in a bizarrely short orbit extremely close to its star. The planet has a year only four days long. “Few had expected that such planets could exist,” Danielsson said. “We had thought that other solar systems would be similar to our own. We were wrong!” The discovery launched a race that has now racked up more than 4,000 known planets orbiting other stars.

James Peebles, Michel Mayor and Didier Queloz

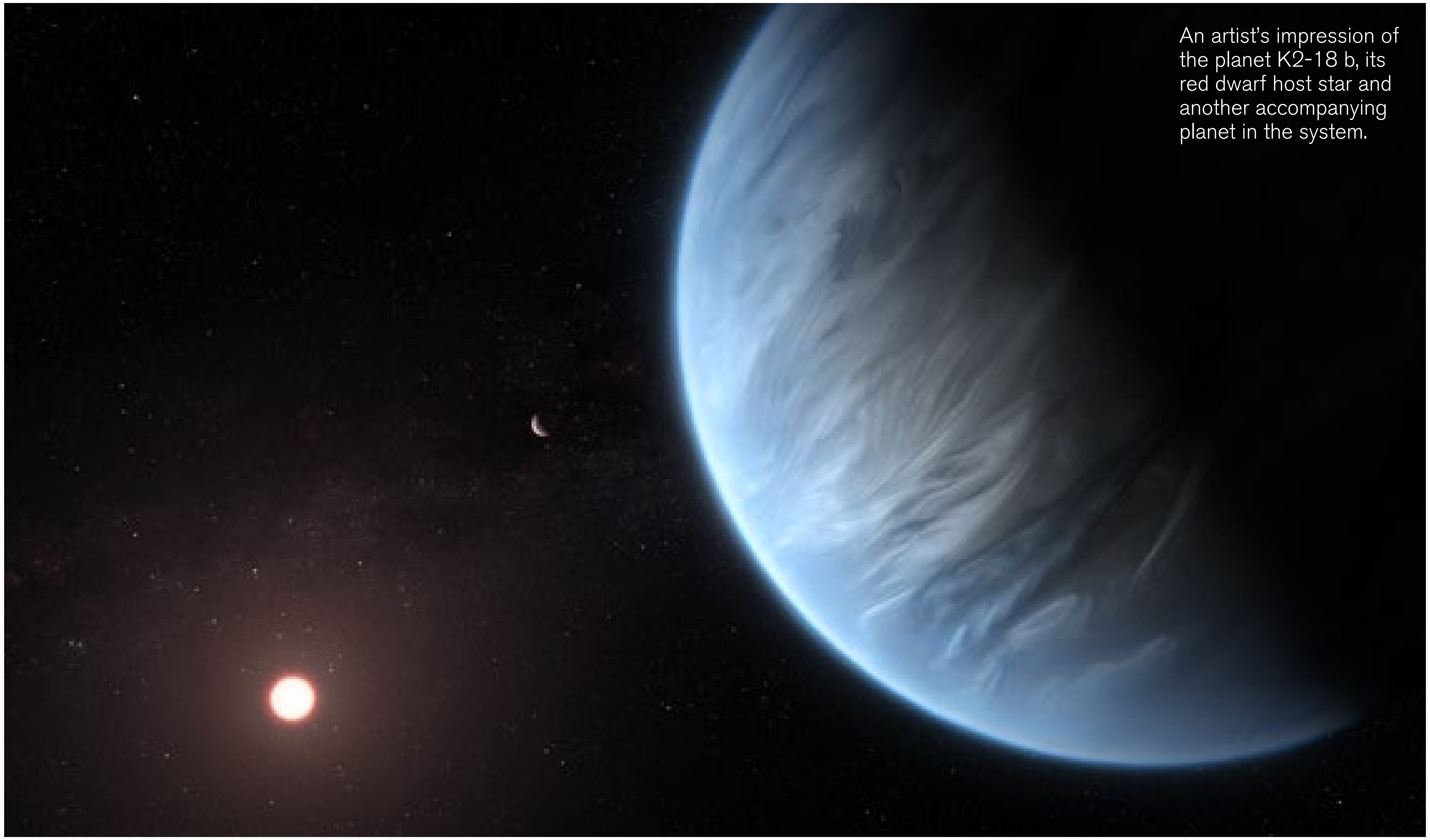
“I cannot be happier about the choice of this year’s recipients,” says astrophysicist and author Mario Livio. “On one hand, the discoveries in cosmology showed that our physical existence is tiny in the grand scheme of things. On the other, Earth is, so far, the only place where we know that life exists. In some sense, the question of whether there is life (and especially complex life) elsewhere may be the most exciting question in science today.”

“It’s a great day for exoplanets,” says Sara Seager, a pioneer in exoplanet studies. “To see a field go from obscure, fringe and laughable to Nobel-worthy is a huge tribute to people all around the world making exoplanets real. In exoplanets, the line between what is considered completely crazy and what is considered mainstream science is constantly shifting. The Nobel award is a cataclysmic shift in the right direction.”

—Clara Moskowitz

Astronomers Find Water on an Exoplanet Twice the Size of Earth

Water vapor in the skies of the world K2-18 b may make it "the best candidate for habitability" currently known beyond our solar system



An artist's impression of the planet K2-18 b, its red dwarf host star and another accompanying planet in the system.

ESA/HUBBLE, M. KORNMESSER

TWENTY YEARS AGO, ALMOST to the day, two competing teams of astronomers independently discovered the first known transiting exoplanet—a world that, viewed from Earth, passed across the face of its star, casting a shadow toward watchful telescopes here. Two decades later transits have become the lifeblood of exoplanet studies, yielding thousands of worlds via space telescopes such as NASA's Kepler and Transiting Exoplanet Survey Satellite (TESS) missions and allowing researchers not only to gauge a planet's size and orbit but also its density and bulk composition. In short, transiting worlds have proved to be the keystones in the burgeoning search for Earth's cosmic twins. Back in 1999, however, the notion that these exoplanetary shadows would be detectable at all was so fantastic that validating it took the separate efforts of two groups.

A similar scenario is now playing out again: Two scientific teams have announced their independent discovery of water—the foundation of biology as we know it—in the atmosphere of a transiting planet dubbed K2-18 b. The planet orbits in the habitable zone of its star, the sweet spot in which starlight may sufficiently warm a world to allow water to pool and flow on its surface. A milestone in the search for alien life, the result portends a near future in which astronomers will use new, advanced telescopes on the ground and in space to more deeply study the most promising planets around our sun's neighboring stars.

"This is the only planet right now that we know outside the solar system that has the correct temperature to support water, that has an atmosphere and that has water in it," says Angelos Tsiaras, an astronomer at University College London and lead author of one of the studies, which was published last September in *Nature Astronomy*. Tsiaras and his colleagues used sophisticated computer models to tease out signs of water vapor on K2-18 b from data gathered by the Hubble Space Telescope, making the planet, he says, "the best candidate for habitability" currently known.

The Hubble data do not speak with significance about the volume of water on K2-18 b—in the planet's upper atmosphere, either a whiff of moisture or an ocean's worth would express a similar signal. Tsiaras and his colleagues suggest the water vapor could make up anywhere between a hundredth of a percent to half of K2-18 b's atmosphere. Pinning down just how much water (as well as other gases, such as methane, carbon dioxide and ammonia) is there will require more broadband observations using future space facilities such as NASA's James Webb Space Telescope, the European Space Agency's Atmospheric Remote-Sensing Infrared Exoplanet Large-Survey (ARIEL) telescope and a nascent generation of extremely large ground-based telescopes.

K2-18 b is slightly more than twice the size of Earth and nearly nine times as massive, likely with a solid core of rock or ice surrounded by an oppressively thick envelope of hydrogen—and other gases, apparently including water vapor. Found by Kepler in 2015, the world nestles in a 33-day orbit around a dim, cool red dwarf star some 110 light-years away, in the constellation of Leo. That star shines with less than 3 percent the luminosity of our own sun, but because K2-18 b orbits so closely to it, the planet receives just 5 percent more starlight than our own. And because the planet transits, some of that starlight passes through its upper atmosphere en route to telescopes here, picking up and transmitting information about the cocktail of gases in K2-18 b's air.

Eight different times between 2016 and 2017, a team led by Björn Benneke of the University of Montreal measured K2-18 b's transitory atmospheric shimmer with the Hubble Space Telescope, as well as with Kepler and the Spitzer

"This is the only planet right now that we know outside the solar system that has the correct temperature to support water, that has an atmosphere and that has water in it."
—Angelos Tsiara

Space Telescope. Hubble data are often released to the public as soon as they are gathered, and in this case, that policy allowed Tsiaras and his co-workers to perform their study. Just like Tsiaras's group, the separate analysis by Benneke's team suggests the existence of a statistically significant fraction of water vapor in K2-18 b's upper atmosphere—but also, uniquely, what the team argues are hints of liquid-water droplets condensing deeper down. That is, Benneke and his colleagues report evidence of clouds—and of rain. Their study has been posted on the preprint server arXiv.org and was submitted to the *Astronomical Journal* for peer-reviewed publication.

"Both studies show there is an atmosphere and water on this planet, which makes the result even stronger," Benneke says. "Finding water vapor is great, but what is so special about K2-18 b is that our models suggest parts of its atmosphere have sufficient temperature and pressure for that vapor to form droplets of liquid water. And these, like in Earth's atmosphere, will form clouds and fall as rain. Just as on Earth, there should be an interplay between condensation and evaporation, an active water cycle between the clouds and the gaseous part of the atmosphere."

The atmospheric region in which the clouds may form, Benneke speculates, could be relatively comfortable, with a pressure of one Earth atmosphere and a temperature not far from that of a typical living room. "In many ways, this planet is not like Earth, but in others, it is very similar. There may be no meaningful 'surface' beneath the thick gas envelope. And even if there is, it would be subjected to very high pressures. It is implausible to imagine something like a human walking around down there—but maybe some sort of extreme microbe could live in those water clouds."

CLOUDY, WITH A CHANCE OF HABITABILITY

Some researchers call K2-18 b and its ilk "super Earths"; others prefer to call them "mini Neptunes." But regardless of nomenclature, the most obvious fact about these objects is that none of them orbit our sun, despite being the most plentiful planetary type in the Milky Way. All we can really know of them currently comes from extrasolar studies. And so far those studies show that most of these planets, somewhere in size between Earth and Neptune, are not very much like Earth at all.

"I like to call them 'hybrid' planets, these worlds with rocky cores and thick hydrogen envelopes," Benneke says. "This is not a bare rock with a thin atmosphere like Earth, but this is also not a giant planet like Neptune or Jupiter."

One appeal of studying such intermediate worlds—many more of which are already being uncovered by the ongoing TESS mission—is the possibility they will reveal something fundamental about how planets of all sizes come to be.

"We think that for planets somewhere around 1.8 times the size of Earth, there is a transition from rocky to gaseous worlds that takes place," says Laura Kreidberg, an astronomer at the Center for Astrophysics at Harvard University and the Smithsonian Institution (CfA), who did not take part in the studies. "K2-18 b is close to that border, so [these studies] are giving us our first glimpse into the atmosphere of a world near this transition."

Nikole Lewis, an astronomer at Cornell University, who was not involved in either paper, notes that this is not the first time signs of water vapor, clouds and perhaps even rain have been seen on worlds outside the solar system. But those earlier discoveries have come from K2-18 b's larger, hotter cousins around other stars, worlds that are more firmly on the "Neptune" side of the planetary divide. "K2-18 b represents a great step on the path to probing cooler and smaller planets," she says. "It has the potential to inform us about how atmospheres form and evolve for planets at or near the habitable zone around red dwarf stars, which will be important for understanding the potential habitability of smaller 'Earth-sized' planets."

Most important, water vapor on K2-18 b would be the best evidence yet that small planets in the habitable zones of red dwarfs can possess atmospheres at all. In some respects, diminutive red dwarfs can punch well above their weight, emitting atmosphere-eroding amounts of radiation that peak early in the stars' lives just when newborn planets may be most vulnerable. And the handful of earlier Hubble studies of tiny, close-in red dwarf worlds have been discouraging: Attempts to study the putative atmospheres of several potentially habitable planets transiting an ultradim red dwarf called TRAPPIST-1 provided inconclusive results. And a more recent probe of LHS 3844 b, a transiting red dwarf world a third larger in size than our own, suggested that planet may well have no air at all.

"The vast majority of the habitable space in the universe may be around red dwarfs because these are the most common stars, and they happen to have lots of rocky planets really close to them," says Nicolas Cowan, an astronomer at McGill University, who is unaffiliated with either of the new papers. "After the study showing LHS 3844 b looks like a dry, barren rock, some of us started getting worried. Maybe red dwarf worlds would turn out to be red herrings for astrobiology."

That concern is why K2-18 b is "a huge deal," Cowan says, despite its distinctly unearthly and somewhat unhospitable state. "It suggests the most common planetary real estate in the universe can also be habitable—not only with atmospheres but with water vapor, too."

Even so, not everyone is convinced the claims of water vapor are much more than hot air. "The statistical significance of the claimed detection is not strong," says David Charbonneau, an astronomer at CfA, who co-discovered the first transiting planet back in 1999. Unlike that finding, which was based on two distinct data sets, the new discovery that was shared between two teams relies on just one—from Hubble, which was never designed to perform such delicate, challenging measurements. "Yes, it is suggestive," Charbonneau says. "But astronomers have been studying transiting planets for 20 years, so I think we are well past the epoch of 'suggestive' studies."

—Lee Billings

Hidden Passage: Could We Spy a Traversable Wormhole in the Milky Way's Heart?

Anomalous motions of stars orbiting our galaxy's central supermassive black hole might reveal the existence of long-hypothesized tunnels through spacetime

Astronomers could soon learn whether a wormhole lurks in the Milky Way's dark heart.

MARK GARLICK *GETTY IMAGES*

WORMHOLES ARE A controversial topic in physics, to say the least. Not only is the idea of traveling through these theoretical passageways between two disparate regions of spacetime debatable, but their very existence is unclear. A forthcoming paper, however, suggests a method to look for a wormhole inside a black hole—and those observations could occur within a decade.

On the preprint server arXiv.org, astrophysicists De-Chang Dai of Yangzhou University in China and Dejan Stojkovic of the University at Buffalo detail a test to determine whether Sagittarius A*, the supermassive black hole at the center of our galaxy, harbors a wormhole. Black holes are thought to be potential homes for wormholes because of the extreme conditions both types of objects have in common. If such a wormhole does exist, they say, any stars lurking at its other side would conceivably exert a subtle but detectable gravitational influence on those at our end. The researchers' paper has been accepted for publication in the journal *Physical Review D.*

"People are talking about wormholes that are traversable," Stojkovic says. "And we said, 'Okay, if particles can go through them, the fields can go as well—like the electromagnetic field and the gravitational field. Then if I'm sitting on one side of the wormhole, I can feel what's on the other one.'"

Stojkovic and Dai say that by monitoring the motions of stars on our side—such as S2, a known star orbiting about 17 light-hours from Sagittarius A*—we could look for tiny but perceptible accelerations caused by a wormhole's presence. If telescopic observations of S2's motion reach a precision of 0.000001 meter per second squared, the duo calculate such measurements could reveal the "imprint" of a star not much larger than our sun pulling on S2 from the wormhole's far side.

If wormholes do exist, there is some question as to whether they link two points in our own universe or in two different parallel universes. For Dai and Stojkovic's purposes, however, the difference is academic because either scenario should produce similar detectable effects. Of course, finding a small acceleration that corresponded to a star on the other side would not be proof of the wormhole's existence, perhaps instead hinting at unseen smaller black holes nearby, for example. But it might point in that direction. If no such acceleration were detected, given the expectation that a supermassive black hole orbited by stars would exist at a wormhole's other side, then the presence of such a passageway in Sagittarius A* could be seemingly ruled out.

"If the mouth is smaller or equal to the [event horizon], then the wormhole is not traversable, because nothing can come out of the horizon."
—Dejan Stojkovic

Cosimo Bambi of Fudan University in China, who was not involved in the paper, notes that a failure to find any anomalous motions could carry implications just as large as those for a success. But he cautions that any excitement about such measurements would be somewhat premature. "Of course, [this study] may be too optimistic," he says. "But in principle, it's possible. We cannot exclude [wormholes], right now, from current observations. Sometimes you discover something even if you don't discover anything."

In order for Stojkovic and Dai's idea to work, any wormhole within Sagittarius A* must lack an event horizon—the boundary beyond which gravity's inexorable pull allows nothing, not even light, to escape—so it would be different from the Einstein-Rosen bridge idea of a black hole on one side and a white hole on the other. "Basically, there is no event horizon," Bambi says. "Here it is just a gate where you can go to the other side and come back. It is true that a black hole, in some cases, can be a wormhole. But in this case, we are talking about traversable wormholes."

Kirill Bronnikov of the People's Friendship University of Russia (RUDN University), who was also not involved in the paper, is similarly cautious about the idea. "In general, it is reasonable," he says. "Bodies moving on one side of a [wormhole] can affect those on the other side." If such a wormhole were located inside a black hole, inside Sagittarius A*, however, the effects of that black hole's event horizon mean we would never know for sure that it was there. "If there is a wormhole instead of a black hole [with an event horizon], then the main idea of this study does not work," he adds.

Stojkovic notes that for the wormhole to be traversable, its "mouth" must be larger than the black hole's event horizon. "An observer outside of the wormhole would just see a black hole that supports the structure of the wormhole," he says. "If the mouth is smaller or equal to the [event horizon], then the wormhole is not traversable, because nothing can come out of the horizon."

Finding out for sure if there is a wormhole at the center of our galaxy might not be beyond the realm of possibility, though. Stojkovic says that as observational methods improve, we could use instruments such as GRAVITY on the Very Large Telescope in Chile to detect wormhole-induced perturbations in S2 that correspond to this idea sooner rather than later. "All we have to do is a little bit better statistical analysis," he says. "Let's say 10 years. It's not crazy. We are almost there."

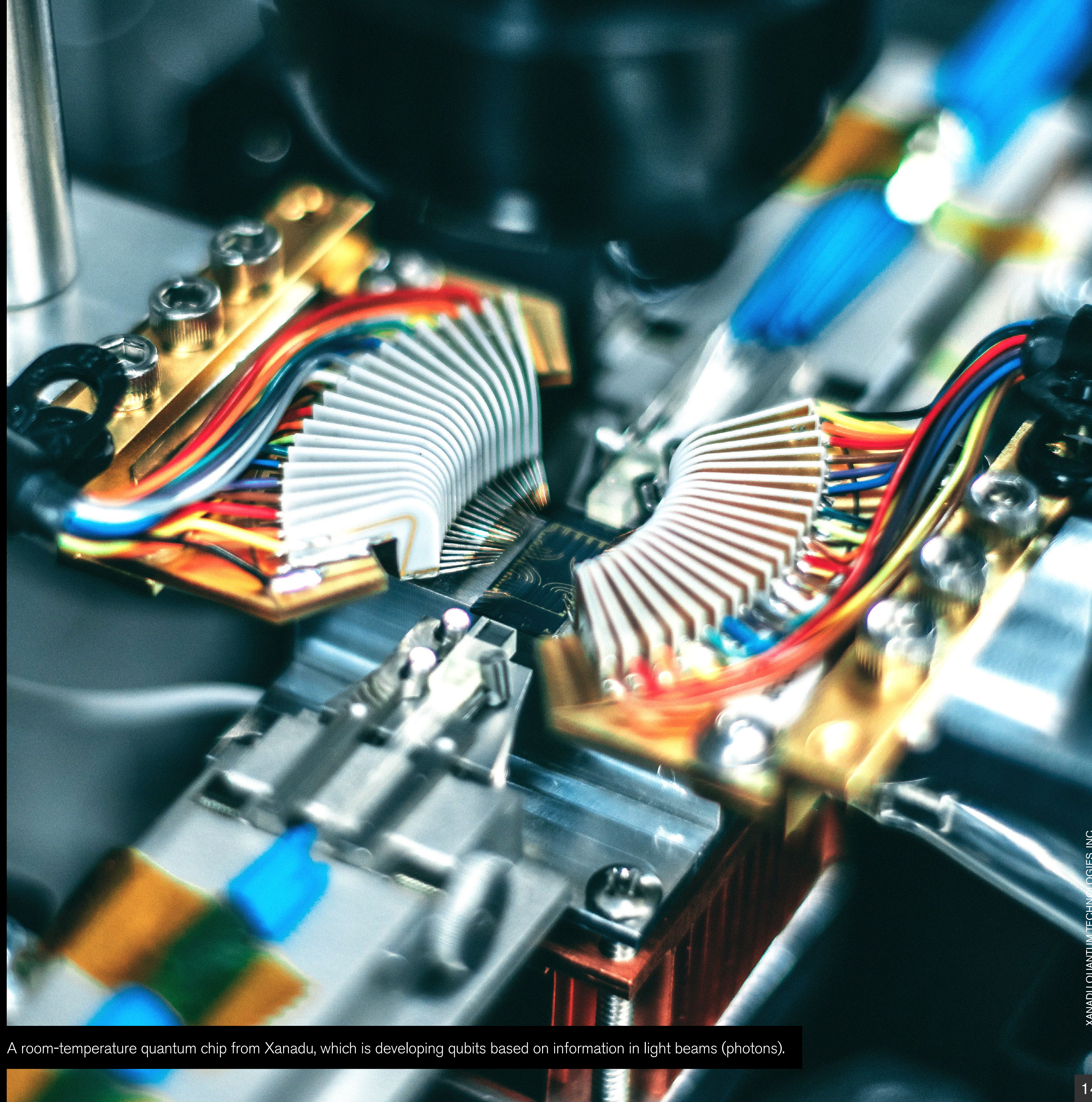
—Jonathan O'Callaghan

SPECIAL REPORT

The Quantum Gold Rush

The science is immature, and a multipurpose quantum computer doesn't yet exist. But that isn't stopping investors from pouring cash into quantum start-ups

By Elizabeth Gibney



A room-temperature quantum chip from Xanadu, which is developing qubits based on information in light beams (photons).

XANADU QUANTUM TECHNOLOGIES, INC.

Elizabeth Gibney works for *Nature* magazine.

ROBERT SCHOELKOPF SPENT MORE THAN 15 YEARS studying the building blocks of quantum computers until, in 2015, he decided it was time to start constructing one. The physicist and his colleagues at Yale University began pitching their start-up firm Quantum Circuits to investors, hoping to persuade venture capitalists that the time was ripe to pour cash into a quantum-computing company. Within two years the team had secured U.S.$18 million. That was enough to build a specialist laboratory—which opened this January—in a science park near the university in New Haven, Conn., and to employ around 20 scientists and engineers.

For Schoelkopf, venture capital (VC) investing was unfamiliar territory. But he's not the only quantum physicist to make a successful sales pitch. Governments and large technology firms have long nurtured quantum research and in the past few years have announced billions of dollars for the field. As their support has ramped up, outside investors have looked to get in early on a fledgling industry.

By the start of 2019, according to an analysis by *Nature*, private investors had funded at least 52 quantum-technology companies globally since 2012—many of them spin-outs from university departments. (Academics have founded many more start-ups that have yet to close deals.) Although the value of some of the cash infusions remains secret, *Nature*'s analysis captures the scale of recent activity. It finds that, in 2017 and 2018, companies received at least $450 million in private funding—more than four times the $104 million disclosed over the previous two years. VC makes up the bulk of this cash. Many firms in the VC hub of California's Silicon Valley have already plunged in, and among the rest, "most are keeping a close eye on quantum," says Christopher Monroe, a physicist at the University of Maryland in College Park, who co-founded the quantum-computing firm IonQ in 2015.

Few doubt that quantum technologies will eventually yield useful and potentially revolutionary products. Alongside government investments, hundreds of firms are rushing to invest in the field, with big names such as IBM, Google, Alibaba, Hewlett Packard, Tencent, Baidu and Huawei all doing their own research. Google has reportedly now created a quantum computer that can solve specialized problems that would stump even the best classical computer—a landmark known as quantum supremacy. Secure encryption using quantum technology is already a commercial product, as are some quantum-enabled technologies that sense, image or measure at exquisitely precise scales. One firm, D-Wave Systems in Burnaby, Canada, even sells computers that exploit quantum effects, although these machines specialize in particular tasks known as optimization problems.

But venture capitalists tend to invest in what they hope will be game changers, such as a multipurpose quantum computer that could handle many kinds of otherwise unfeasible calculations. From the perspective of investors, the cash pumped into the field annually represents a small outlay so far—on a par with VC investments in artificial-intelligence (AI) firms before 2010, for instance. (By 2018 U.S. VC investments in AI had boomed to $9.3 billion.) Still, these numbers are substantial for an immature field that doesn't yet have much to sell. Despite this, some software firms are already marketing their work on quantum algorithms, which are written for hardware that does not yet exist.

Many worry that the buzz could turn into a bubble.

"There is a lot of hype right now," says Doug Finke, a computer scientist in Orange County, California, who runs the industry-tracking Web site Quantum Computing Report. Quantum technologies have seen rapid progress, but machines that can tackle many kinds of computation are still likely to be decades away, and even then it will be difficult to write algorithms that harness their abilities, Finke says.

Some VC investors are betting on a breakthrough that brings general-purpose quantum computers to fruition in five or 10 years. Others are banking on making just enough progress for another firm to buy them out. Many also hope scientists can find applications for relatively small, imperfect quantum computers, which might emerge sooner. These would be limited to tackling specific questions, such as simulating a reaction in quantum chemistry or optimizing a financial model. They might not perform better than a classical computer that has unlimited computing resources, but they could still create marketable products.

If these early quantum computers don't emerge soon with profitable uses, the field could face a "valley of death" in which investment falters, warned a December 2018 report from the U.S. National Academies of Science, Engineering, and Medicine. Some researchers worry about a "quantum winter" similar to the "AI winters" used to describe the lulls that followed surges of interest in that field. There are now hints that U.S. firms are finding it harder to get private funding, says Finke, who notes that seven out of 10 deals he has documented this year were outside the country. "There is still a lot of value being created—it's just a case of whether there is too much hype," says Christian Weedbrook, founder of the quantum-computing firm Xanadu based in Toronto.

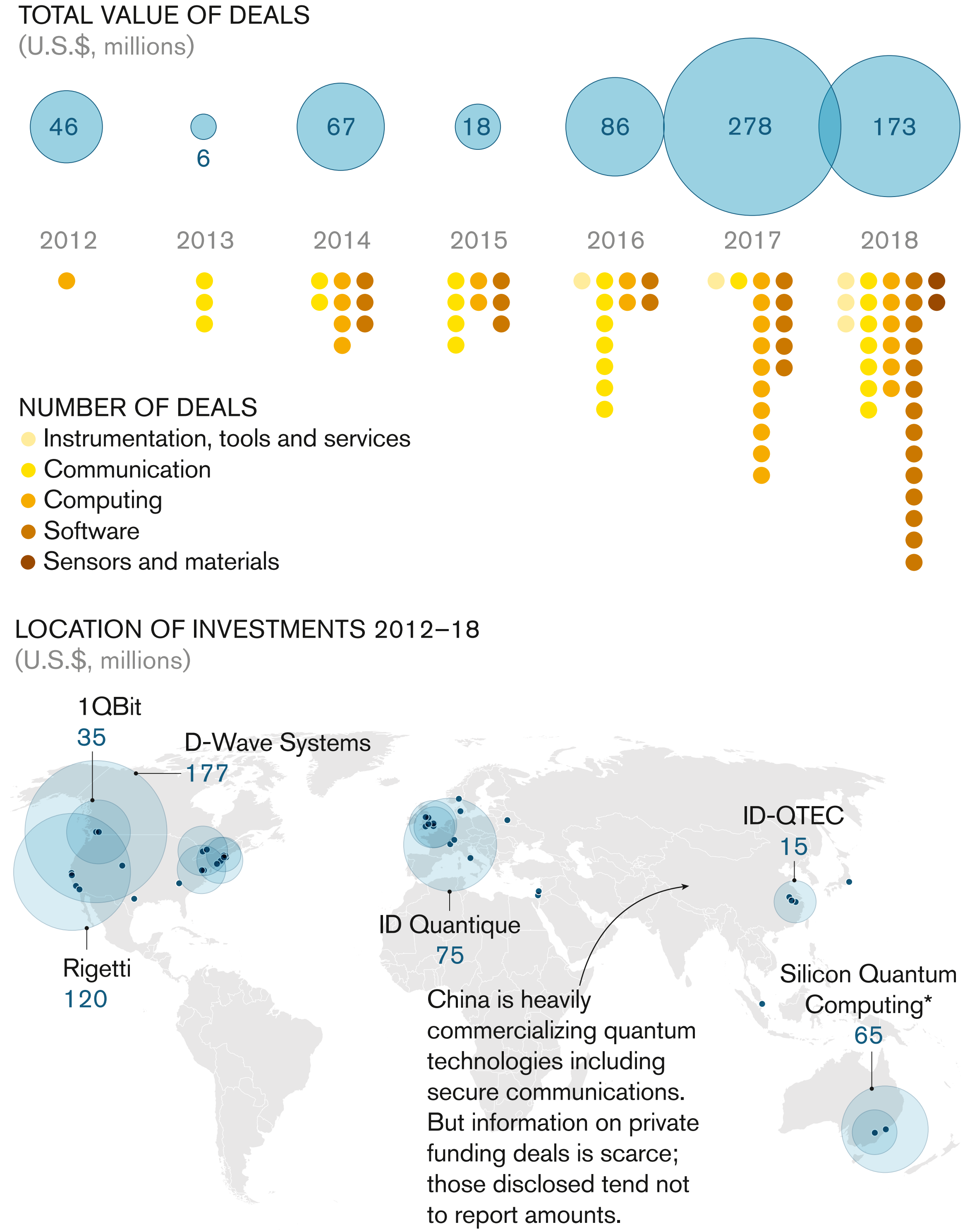
QUIDS IN FOR QUBITS

Quantum technologies have already transformed daily life. Computers, mobile phones, medical imaging, lasers and superconductors all emerged from the scientific revolution of the early 20th century, when physicists unlocked the inner workings of the atom through quantum mechanics. But today's generation of quantum technologies go further by manipulating previously untapped and often fragile quantum phenomena. These include superposition, in which particles seem to have multiple states until they are observed, and entanglement, which describes how the properties of quantum systems—such as particles' spin and polarization—can be inextricably tied together.

Such quantum technologies include unhackable encryption, supersensitive detection devices and new forms of imaging. The biggest game changer, if scientists can pull it off, would be a general-purpose quantum computer. By entangling collections of quantum bits, or "qubits," such a machine could perform calculations such as searching databases and factoring large numbers dramatically faster than the best classical computers can. "There is a whole class of problems that will always be impossible

Cash for Qubits

A growing number of quantum technology firms are raising cash from private investors, particularly in the sectors of quantum computing and quantum software.



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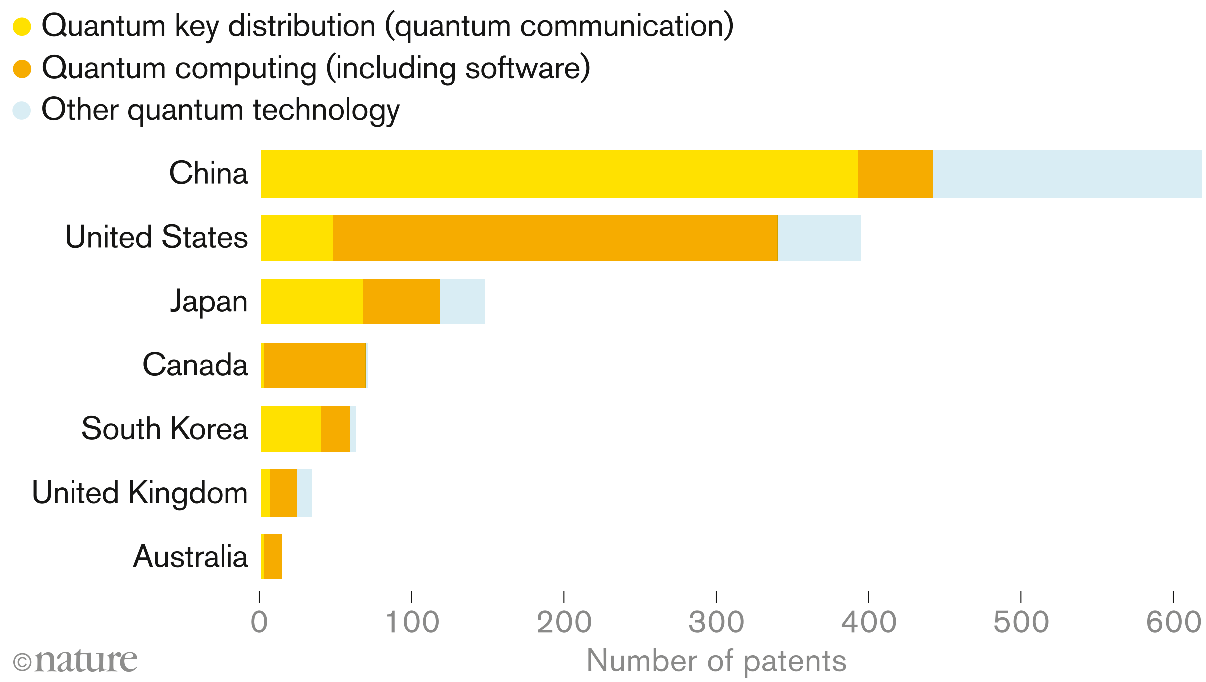
NATURE ANALYSIS, INCLUDING DATA FROM QUANTUM COMPUTING REPORT, BOSTON CONSULTING GROUP, PITCHBOOK AND CRUNCHBASE unless we have quantum computers," Monroe says.

Quantum Patents

An analysis of global patents in quantum technology since 2012 shows China dominating quantum communication, but North America ahead on quantum computing.



To analyze commercial deals in the field, *Nature* cross-referenced details of quantum start-ups published on market-research Web sites and in consultancy reports, together with information provided by PitchBook, a market-research firm in Seattle.

Firms developing the physical qubits—the hardware of quantum computing—have received the lion's share of VC investment. Schoelkopf's company uses tiny loops of superconducting wire chilled to close to absolute zero for its qubits. This is the most intensively studied setup for quantum-computing hardware: technology giants Google and IBM, for instance, use the same principles. (Internal research investments by big tech firms are likely to be large but are not publicly disclosed and so are not included in our analysis.) Google's biggest quantum computer has 72 qubits, but around one million will be needed for a general-purpose quantum computer. Monroe's firm uses another long-standing technology: applying magnetic fields to trap ions of ytterbium whose quantum state is read out using lasers.

Other companies focus on different hardware that is at an earlier stage of development but that might prove easier to manufacture at scale. These are increasingly attracting investments, says Christophe Jurczak, founder and managing partner of Quantonation, a Paris-based venture fund that launched in 2018 and focuses on "deep physics" start-ups. Companies developing qubits based on light and on silicon have received VC investment on the scale of tens of millions of dollars since 2017.

One firm—PsiQuantum in Palo Alto, Calif.—is promising to leapfrog its competitors to create a million-qubit computer in about eight years. Its unusual idea involves making qubits from photons of light guided through grooves etched into silicon chips. The advantage of this approach is that these qubits could be made in existing semiconductor manufacturing plants, says chief executive Jeremy O'Brien, who left his tenured position at the University of Bristol, U.K., to co-found the firm in 2016. Although other academics remain skeptical about the company's claims, O'Brien says it is among the "top handful" of quantum companies in terms of investment and now employs a workforce of around 100. That might suggest it has raised dozens of millions of dollars, although the company won't publicly say so.

Quantum software is also proving a lure for private investment, with 20 firms raising more than $110 million across 28 deals from 2012 to the end of 2018. These companies are crafting algorithms that translate problems—such as optimizing the logistics of supply chains or simulating molecules for drug discovery—into software that could be run on early quantum computers. Money for software tends to come from "strategic" VC firms that are part of large corporations. These fund start-ups with the aim of both developing the technology and making profits, says Matt Johnson, chief executive and co-founder of quantum software firm QC Ware in Palo Alto, which raised $6.5 million in 2018. Purely profit-driven VCs aren't so interested yet, he says.

Several software start-ups have raised tens of millions of dollars each—including Zapata Computing in Cambridge, Mass.; 1QBit in Vancouver, Canada; and U.K.-based Cambridge Quantum Computing. Although no one is yet benefiting from quantum algorithms, some firms are willing to pay to develop them, says Yianni Gamvros, head of business development at QC Ware. That company has already signed contracts in industries such as aerospace, which plans decades ahead, and in finance, where tiny advantages can bring huge gains. The firm is developing algorithms that, on an early quantum computer, could solve those industries' biggest bottlenecks, he says. Many of the companies are still reeling from the impact of AI on their business. "This seems like a small investment to get ready for another potentially disruptive force," Gamvros says.

Computing isn't the only quantum technology attracting funds. Swiss start-up Qnami in Basel, which received $130,000 in 2018 to develop a quantum magnetic micro-

MARTINO TRAVAGNIN/EC JOINT RESEARCH CENTER scope using single electrons trapped in synthetic diamond, is one of at least three firms that have raised relatively small amounts of private cash to produce imaging or sensing technologies.

And it's hard to quantify the investments in one of the hottest quantum fields: communications, which uses entangled photons to create cryptographic keys that enable fundamentally secure data transmission. Thirteen firms that work on secure quantum communications have announced 27 deals that raised cash, but only around half disclosed amounts. The leaders in the field—Chinese firms QuantumCTek in Heifei City and Qasky in Wuhu City, both in Anhui province—have not revealed how much private funding they have received.

In Switzerland, ID Quantique in Geneva installed its first short-range system for the quantum encryption of ballot information in regional elections in 2007. Now Chinese engineers are taking quantum communications global: expanding on a 2,000-kilometer quantum link that was installed in 2014 and developing a network of quantum satellites after launching the first such craft in 2016. If quantum computers gain the ability to hack the best classical encryption, quantum encryption might prove the only route for secure communications.

QUANTUM GEOGRAPHY

North America has long been the world's leader in attracting VC cash, and *Nature*'s analysis shows that the region also dominates private quantum investment. But the boom is not restricted to Silicon Valley. Firms in Canada have attracted $243 million, led by quantum-computing pioneer D-Wave Systems, which alone has raised $177 million. A whole ecosystem has emerged to support quantum companies around academic hubs in Waterloo and Toronto, which have benefited from public and philanthropic investment, tax advantages and successful incubators, Jurczak says. "You get very good vibes and connections there," he says. A perceived immigration crackdown in the U.S. is also giving Canada an advantage in attracting talented quantum physicists, says Xanadu's Weedbrook. "We're seeing a reverse brain drain to Canada, and that's been great for us," he says.

"There is a whole class of problems that will always be impossible unless we have quantum computers."
—Christopher Monroe

The biggest gap in *Nature*'s analysis is caused by a lack of investment information from China. Reports in English-language media and by Western analytics firms rarely cover deals in China, which often involve state-backed VC firms, so our analysis is likely to miss a large number of contracts there. And in our data, only one in 10 fundraising deals secured by Chinese firms disclosed its value. Commercialization is well underway for many quantum technologies in China, says quantum physicist Jian-Wei Pan of the University of Science and Technology of China in Hefei; QuantumCTek was launched as a spinout from his lab in 2009.

Patents offer another sign of the activity in China. More than 43 percent of quantum-technology innovations patented between 2012 and 2017 came from Chinese firms and universities, according to data gathered by the European Commission's Joint Research Center in Ispra, Italy. In patenting, China "has been extremely aggressive, especially in areas having to do with communication," says Celia Merzbacher, associate director of the U.S. Quantum Economic Development Consortium in Arlington, Va.

Elsewhere around the world, private funding mirrors research hotspots—with pockets of investment in Australia, Singapore, the U.K. and across Europe. European investors are typically more risk-averse and have smaller budgets, but a €1-billion (U.S.$1.1-billion) flagship, launched by the European Union in 2018, aims to ensure that the region's strengths in basic research translate to commercial success. Through similar public-investment initiatives, the U.S., U.K., Japan, Sweden, Singapore, Canada and China are all plowing hundreds of millions of dollars into quantum technologies.

QUANTUM BOTTLENECK

Most university scientists who have founded start-ups, such as Schoelkopf, still spend time on campus, continuing research that could lead to further breakthroughs down the line. Only a few, such as PsiQuantum's O'Brien, have left academia entirely. Even so, the boom in quantum start-ups means that there are already too few highly qualified quantum engineers to supply the firms—and the industry, such as it is, risks draining academic talent away from universities, as happened in AI, says Weedbrook says. "I think we're starting to hit a point where we're concerned about it," he says. More training is needed: a major strand of the $1.2-billion U.S. National Quantum Initiative, which President Donald Trump signed in December 2018, is to train a new generation in quantum-related jobs.

At the same time, some firms are overpromising on the technology they can deliver, Monroe says. "There's a lot of hype in the field, a lot of promises that on the face of it look a little ridiculous, and some of that gets funded," he says.

Researchers wouldn't name particular efforts they felt were hyped, but Weedbrook pointed to the scale of investment in companies that focus only on quantum software as a sign of an investment bubble; some of them have raised tens of millions of dollars, even though they incur few costs for physical equipment or facilities. "It's amazing amounts being raised, so it seems to indicate that there is a lot of hype," says Weedbrook, whose firm develops both quantum hardware and software.

But quantum-software firms argue that their work needs cash for both intensive development and to hire staff. Companies must also cover their costs for longer than the two-year period that a typical funding round is expected to support, says Christopher Savoie, chief executive of Zapata Computing, a quantum-software firm that raised $21 million earlier in 2019. This is because it remains uncertain when hardware for quantum software will emerge and because firms need funding to lure scientists away from stable academic positions, he says.

Not everyone is so concerned. O'Brien says that although VC firms might meet with researchers on the basis of buzz, he hasn't yet seen that translate into bad decisions. And although quantum physics can seem counterintuitive, these technologies are not inherently harder to understand than many others, he says. "There's some weird and wacky stuff going on, but there's weird and wacky stuff going on in a transistor."

If 2019 data end up showing that private U.S. investment in quantum technology is slowing down, Finke says, that might be because of fears of a quantum winter or the long time line to profitability for quantum firms. Increased competition between the large number of start-ups could also play a part, as well as concerns that the U.S.-China trade war might cool the economy, he adds. A hype cycle is mandatory for almost every high-tech market, says Merzbacher, who predicts that "breathless reporting and frothy announcements" are likely to die down. There are solid reasons to think that quantum technologies will create game-changing advances. "It's a question of the time line, rather than if that will happen," she says.

Schoelkopf says that some firms are making grand promises on too short a time line. But he thinks that estimates on how long it will take to build a general-purpose quantum computer are overly pessimistic. "If you had projected forward from where we were 10 years ago, you would never have predicted how far we are today," he says. Innovative hardware combined with software that picks out the most tractable problems means "we're going to be reaching useful quantum computations faster than people think."

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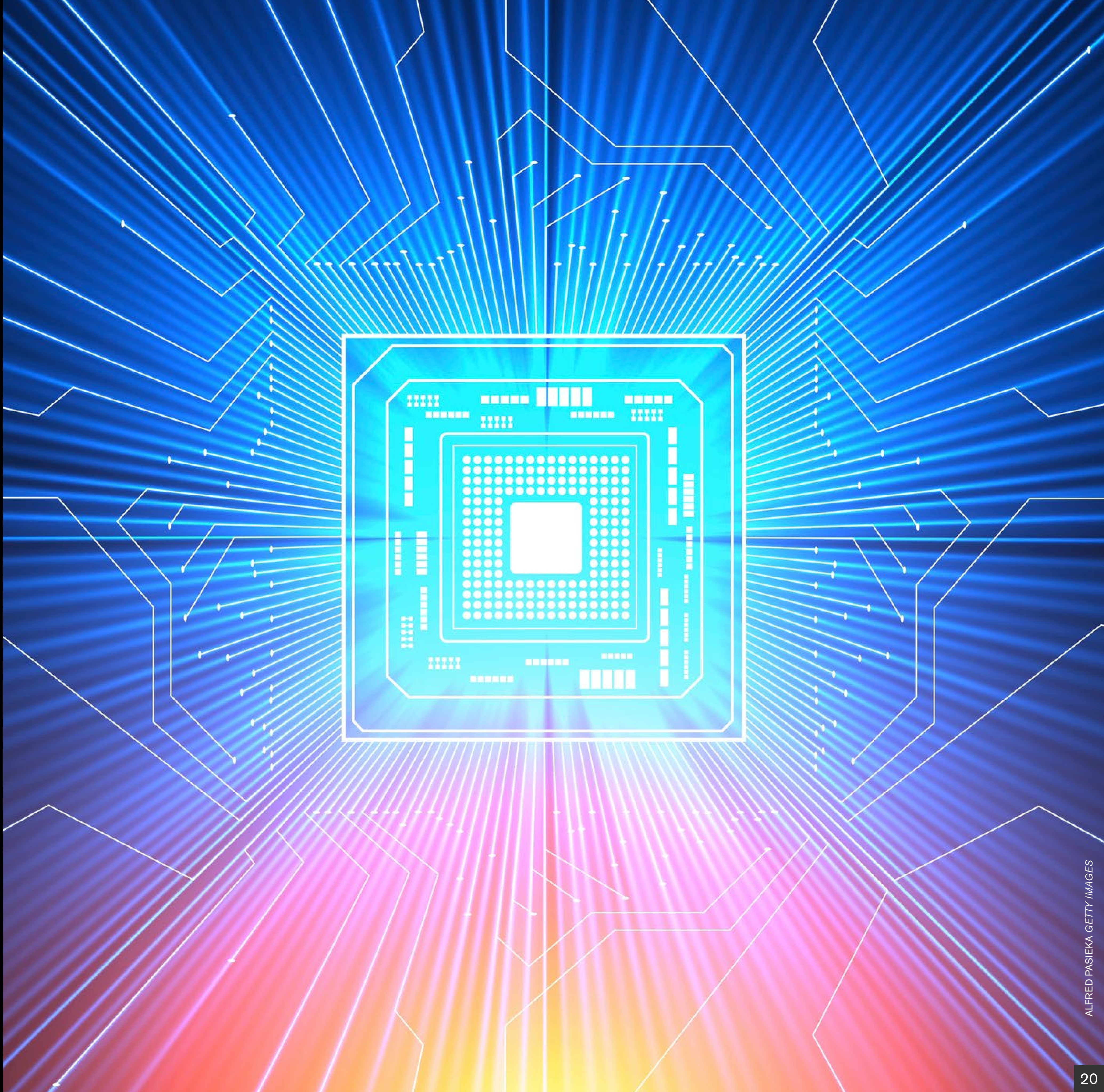
SPECIAL REPORT

Beyond Quantum Supremacy: The Hunt for Useful Quantum Computers

Researchers look for ways to put today's small noisy quantum systems to work

By Michael Brooks



ALFRED PASIEKA *GETTY IMAGES*

Michael Brooks is a freelance writer based in the U.K.

JUST OCCASIONALLY, ALÁN ASPURU-GUZIK HAS A MOVIE-STAR moment, when fans half his age will stop him in the street. "They say, 'Hey, we know who you are,'" he laughs. "Then they tell me that they also have a quantum start-up and would love to talk to me about it." He doesn't mind a bit. "I don't usually have time to talk, but I'm always happy to give them some tips."

That affable approach is not uncommon in the quantum-computing community, says Aspuru-Guzik, who is a computer scientist at the University of Toronto and co-founder of the quantum-computing company Zapata Computing in Cambridge, Mass. Although grand claims have been made about a looming revolution in computing, and private investment has been flowing into quantum technology, it is still early days, and no one is sure whether it is even possible to build a useful quantum computer.

Today's quantum machines have at best a few dozen quantum bits, or qubits, and they are often beset by computation-destroying noise. Researchers are still decades—and many thousands of qubits—away from general-purpose quantum computers, ones that could do long-heralded calculations such as factoring large numbers. A team at Google has now reportedly demonstrated a quantum computer that can outperform conventional machines, but such "quantum supremacy" is expected to be extremely limited. For general applications, 30 years is "not an unrealistic timescale," says physicist John Preskill of the California Institute of Technology.

Some researchers have raised the possibility that, if quantum computers fail to deliver anything of use soon, a quantum winter will descend: enthusiasm will wane, and funding will dry up before researchers get anywhere close to building full-scale machines. "Quantum winter is a real concern," Preskill says. But he remains upbeat because the slow progress has forced researchers to adjust their focus and see whether the devices they already have might be able to do something interesting in the near future.

Judging from a flurry of papers published over the past few years, it's a definite possibility. This is the era of the small, error-prone, or "noisy intermediate-scale quantum" (NISQ), machine, as Preskill has put it. And so far it has turned out to be a much more interesting time than anyone had anticipated. Although the results are still quite preliminary, algorithm designers are finding work for NISQ machines that could have an immediate impact in chemistry, machine learning, materials science and cryptography—offering insights into the creation of chemical catalysts, for example. What's more, these innovations are provoking unexpected progress in conventional computing. All this activity is running alongside efforts to build bigger, more robust quantum systems. Aspuru-Guzik advises people to expect the unexpected. "We're here for the long run," he says. "But there might be some surprises tomorrow."

FRESH PROSPECTS

Quantum computing might feel like a 21st-century idea, but it came to life the same year that IBM released its first personal computer. In a 1981 lecture, physicist Richard Feynman pointed out that the best way to simulate real-world phenomena that have a quantum-mechanical basis, such as chemical reactions or the properties of semiconductors, is with a machine that follows quantum-mechanical rules.

Such a computer would make use of entanglement, a phenomenon unique to quantum systems. With entanglement, a particle's properties are affected by what happens to other particles with which it shares intimate quantum connections. These links give chemistry and many branches of materials science a complexity that defies simulation on classical computers. Algorithms designed to run on quantum computers aim to make a virtue of these correlations, performing computational tasks that are impossible on conventional machines.

But the same property that gives quantum computers such promise also makes them difficult to operate. Noise in the environment, whether from temperature fluctuations, mechanical vibrations or stray electromagnetic fields, weakens the correlations between qubits, the computational units that encode and process information in the computer. That degrades the reliability of the machines, limits their size and compromises the kinds of computation that they can perform.

One potential way to address the issue is to run error-correction routines. But such algorithms require their own qubits—the theoretical minimum is five error-correcting qubits for every qubit devoted to computation—adding a lot of overhead costs and further limiting the size of quantum systems. Some researchers are focusing on hardware. Microsoft Quantum, a multinational team, is attempting to use exotic, "topological particles" in extremely thin semiconductors to construct qubits that are much more robust than today's quantum systems.

But these work-arounds are longer-term projects, and many researchers are focusing on what can be done with the noisy, small-scale machines that are available now—or will be in the next five to 10 years. Instead of aiming for a universal, error-corrected quantum computer, for example, physicist Pan Jian-Wei and his team at the University of Science and Technology of China in Hefei are pursuing short- and mid-term targets. That includes quantum supremacy and developing quantum-based simulators that can solve meaningful problems in areas such as materials science. "I usually refer to it as 'laying eggs along the way,'" he says.

Bert de Jong of Lawrence Berkeley National Laboratory has his eye on applications in chemistry, such as finding alternatives to the Haber process for the manufacture of ammonia. At the moment, researchers must make approximations to run their simulations on classical machines, but that approach has its limits. "To enable large scientific advances in battery research or any scientific area relying on strong electron correlation," de Jong says, "we cannot use the approximate methods." NISQ systems won't be able to perform full-scale chemistry simulations. But when combined with conventional computers, they might demonstrate an advantage over existing classical simulations. "The classically hard part of the simulation is solved on a quantum processor, while the rest of the work is done on a classical computer," de Jong says.

"The classically hard part of the simulation is solved on a quantum processor, while the rest of the work is done on a classical computer."
—Bert de Jong

This kind of hybrid approach is where Aspuru-Guzik earned his fame. In 2014 he and his colleagues devised an algorithm called the variational quantum eigensolver (VQE), which uses conventional machines to optimize guesses. Those guesses might be about the shortest path for a traveling salesperson, the best shape for an aircraft wing or the arrangement of atoms that constitutes the lowest energy state of a particular molecule. Once that best guess has been identified, the quantum machine searches through the nearby options. Its results are fed back to the classical machine, and the process continues until the optimum solution is found. As one of the first ways to use NISQ machines, VQE had an immediate impact, and teams have used it on several quantum computers to find molecular ground states and explore the magnetic properties of materials.

That year Edward Farhi, then at the Massachusetts Institute of Technology, proposed another heuristic, or best-guess, approach called the quantum approximation optimization algorithm (QAOA). The QAOA, another quantum-classical hybrid, performs what is effectively a game of quantum educated guessing. The only application so far has been fairly obscure—optimizing a process for dividing up graphs—but the approach has already generated some promising spin-offs, says Eric Anschuetz, a graduate student at M.I.T., who has worked at Zapata.

One of those, devised by Anschuetz and his colleagues, is an algorithm called variational quantum factoring (VQF), which aims to bring the encryption-breaking, large-number-factoring capabilities of quantum processing to NISQ-era machines. Until VQF, the only known quantum algorithm for such work was one called Shor's algorithm. That approach offers a fast route to factoring large numbers, but it is likely to require hundreds of thousands of qubits to go beyond what is possible on classical machines. In a paper published in 2019, Zapata researchers suggest that VQF might be able to outperform Shor's algorithm on smaller systems within a decade. Even so, no one expects VQF to beat a classical machine in that time frame.

Others are looking for more general ways to make the most of NISQ hardware. Instead of diverting qubits to correct noise-induced errors, for example, some researchers have devised a way to work with the noise. With "error mitigation," the same routine is run on a noisy processor multiple times. By comparing the results of runs of different lengths, researchers can learn the systematic effect of noise on the computation and estimate what the result would be without noise.

The approach looks particularly promising for chemistry. In March a team led by physicist Jay Gambetta of IBM's Thomas J. Watson Research Center showed that error mitigation can improve chemistry computations performed on a four-qubit computer. The team used the approach to calculate basic properties of the molecules hydrogen and lithium hydride, such as how their energy states vary with interatomic distance. Although single, noisy runs did not map onto the known solution, the error-mitigated result matched it almost exactly.

Errors might not even be a problem for some applications. Vedran Dunjko, a computer scientist and physicist at the University of Leiden in the Netherlands, notes that the kinds of tasks performed in machine learning, such as labeling images, can cope with noise and approximations. "If you're classifying an image to say whether it is a human face or a cat or a dog, there is no clean mathematical description of what these things look like—and nor do we look for one," Dunjko says.

FUZZY FUTURE

Gambetta's team at IBM has also been pursuing quantum machine learning for NISQ systems. Earlier in 2019, working with researchers at the University of Oxford and at M.I.T., the group reported two quantum machine-learning algorithms that are designed to pick out features in large data sets. It is thought that as quantum systems get bigger, their data-handling capabilities should grow exponentially, ultimately allowing them to handle many more data points than classical systems can. The algorithms provide "a possible path to quantum advantage," the team wrote. But as with other examples in the machine-learning field, no one has yet managed to demonstrate a quantum advantage.

In the era of NISQ computing, there is always a "but." Zapata's factoring algorithm, for instance, might never factor numbers faster than classical machines. No experiments have been done on real hardware yet, and there is no way to definitively, mathematically prove superiority.

Other doubts are arising. Gian Giacomo Guerreschi and Anne Matsuura of Intel Labs in Santa Clara, Calif., performed simulations of Farhi's QAOA algorithms and found that real-world problems with realistically modeled noise do not fare well on machines the size of today's NISQ systems. "Our work adds a word of caution," says Giacomo Guerreschi. "If order-of-magnitude improvements to the QAOA protocols are not introduced, it will take many hundreds of qubits to outperform what can be done on classical machines."

One general problem for NISQ computing, Dunjko points out, comes down to time. Conventional computers can effectively operate indefinitely. A quantum system can lose its correlations, and thus its computing power, in fractions of a second. As a result, a classical computer does not have to run for very long before it can outstrip the capabilities of today's quantum machines.

NISQ research has also created a challenge for itself by focusing attention on the shortcomings of classical algorithms. It turns out that many of those, when investigated, can be improved to the point at which quantum algorithms can't compete. In 2016, for instance, researchers developed a quantum algorithm that could draw inferences from large data sets. It is known as a type of recommendation algorithm because of its similarity to the "you might also like" algorithms that are used online. Theoretical analysis suggested that this scheme was exponentially faster than any known classical algorithm. But in July 2018 computer scientist Ewin Tang, then an undergraduate student at the University of Texas at Austin, formulated a classical algorithm that worked even faster.

Tang has since generalized her tactic, taking processes that make quantum algorithms fast and reconfiguring them so that they work on classical computers. This has allowed her to strip the advantage from a few other quantum algorithms, too. Despite the thrust and parry, researchers say it is a friendly field and one that is improving both classical computing and quantum approaches. "My results have been met with a lot of enthusiasm," says Tang, who is now a Ph.D. student at the University of Washington.

For now, however, researchers must contend with the fact that there is still no proof that today's quantum machines will yield anything of use. NISQ could simply turn out to be the name for the broad, possibly featureless landscape researchers must traverse before they can build quantum computers capable of outclassing conventional ones in helpful ways. "Although there were a lot of ideas about what we could do with these near-term devices," Preskill says, "nobody really knows what they are going to be good for."

De Jong, for one, is okay with the uncertainty. He sees the short-term quantum processor as more of a lab bench—a controlled experimental environment. The noise component of NISQ might even be seen as a benefit because real-world systems, such as potential molecules for use in solar cells, are also affected by their surroundings. "Exploring how a quantum system responds to its environment is crucial to obtaining the understanding needed to drive new scientific discovery," he says.

For his part, Aspuru-Guzik is confident that something significant will happen soon. As a teenager in Mexico, he used to hack phone systems to get free international calls. He says he sees the same adventurous spirit in some of the young quantum researchers he meets—especially now that they can effectively "dial in" and try things out on the small-scale quantum computers and simulators made available by companies such as Google and IBM. This ease of access, he thinks, will be key to working out the practicalities. "You have to hack the quantum computer," he says. "There is a role for formalism, but there is also a role for imagination, intuition and adventure. Maybe it's not about how many qubits we have; maybe it's about how many hackers we have."

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SPECIAL REPORT

New Encryption System Protects Data from Quantum Computers

As quantum computing creeps closer, IBM successfully demonstrates a way to secure sensitive information

By Sophie Bushwick

A functional quantum computer could overcome current encryption methods.

Sophie Bushwick is an associate editor who covers technology at *Scientific American*.

ONCE QUANTUM COMPUTERS BECOME functional, experts warn, they could perform calculations exponentially faster than classical computers—potentially enabling them to destroy the encryption that currently protects our data, from online banking records to personal documents on hard drives. That's why the National Institute of Standards and Technology (NIST) is already pushing researchers to look ahead to this "postquantum" era. Most recently, IBM successfully demonstrated a quantum-proof encryption method it developed.

To send secure messages online or encrypt the files on a computer, most modern systems employ asymmetric, or public-key, cryptography. With this technique, data are encoded with a so-called public key, which is accessible to all; decoding that information requires a private key that only one party knows. Although both parts of this system are called keys, the public key is more like a slotted lockbox: anyone can drop something in, or encode a secret message, but only the private key's holder can unlock the box, or decrypt the message. This arrangement makes such asymmetric cryptography more secure than a symmetric system—one that is more like an unlocked lockbox (security depends on keeping the box hidden because a person who can get to it to drop in a message can also access its contents). Think of symmetric cryptography as a more complex version of a substitution cipher: if the message is encoded by shifting each letter of the alphabet ahead by three places, one can crack the code by simply shifting each letter *back* by three. That ability means anyone who knows how to put the code in place can also reverse engineer it. In contrast, public-key cryptography uses a mathematical algorithm to generate much more complex keys so the code cannot be run backward in this way. Different public-key systems can utilize different algorithms, as long as they are based on mathematical problems that are easy to put into place but hard to reverse engineer. For instance, any computer can multiply two extremely large prime numbers together, yet factoring the result is nearly impossible—at least, it would be for a classical machine.

"There are a lot of problems that cryptography is based on right now that, actually, we don't think can be solved by normal computers," says Vadim Lyubashevsky, a quantum-safe cryptography researcher at IBM Research–Zurich. But many of these encryption algorithms (including those that rely on multiplying two large prime numbers together) were originally developed decades ago, before researchers had developed quantum algorithms that could outperform classical ones. "As it so happens, [quantum computers] can solve the sort of these cryptographic problems on which we built our cryptography in the 1980s exponentially faster than classical computers," Lyubashevsky says.

There are, however, still equations that quantum algorithms have not yet managed to solve. "People have kind of assumed that quantum computers are a generalized speedup of conventional computers—that they somehow can do everything a conventional computer can do but much faster. And that's not actually true," says Alan Woodward, a professor of computer science at the University of Surrey in England, who is not involved in IBM's research. "There is quite a limited set—four types of algorithms we know so far—[that] they can do faster than conventional computers." Unfortunately, though, this limited set is still enough to threaten the current encryption infrastructure to some degree. In particular, a quantum technique called Shor's algorithm can factor large numbers exponentially faster than classical machines. That ability means a quantum computer could crack systems like RSA, a widely used method for encrypting data.

Rather than waiting for a quantum computer to perform this feat (which may not happen for another decade or longer), teams of researchers, including Lyubashevsky and his colleagues, are scrambling to find new encryption methods that quantum computers cannot manipulate, based on more secure equations. "The working assumption is that if you can find one of these mathematical problems that are easy to do one way but difficult to do the other way—and it's not solvable as part of the hidden subgroup problem—then it should be capable of withstanding attack by quantum computers," Woodward says. A "hidden subgroup problem" describes a category that includes the problem of breaking numbers down to their prime factors. "While quantum computers can do some things better against a particular set of problems, there are tons of other things they just do not help with—almost at all," Lyubashevsky says. "So these are the types of problems that people are trying to build cryptography on."

Because there are many of these types of problems, organizations such as NIST are trying to narrow down the potential options in order to develop a standardized method for quantum-proof encryption. In 2016 NIST put out a call for potential postquantum algorithms, and earlier in 2019 it announced it had winnowed 69 accepted submissions down to 26 leading candidates. The plan is to select the final algorithms in the next couple of years and to make them available in draft form by 2024. IBM is not waiting for the results of this competition, however. Last August the company announced its researchers had used its NIST submission, a system dubbed CRYSTALS (short for Cryptographic Suite for Algebraic Lattices) to successfully encrypt a magnetic-tape storage drive.

CRYSTALS generates its public and private keys with a category of equations called lattice problems. Although researchers have studied these equations since the 1980s, they have not developed either classical or quantum algorithms capable of defeating them. According to Lyubashevsky, one simple example of such a problem is to add three out of a set of five numbers together, give the sum to a friend and then ask that second party to determine which three numbers were added. "Of course, with five numbers, it's not hard," Lyubashevsky says. "But now imagine 1,000 numbers with 1,000 digits each, and I pick 500 of these numbers."

IBM submitted CRYSTALS to the NIST contest in 2017. Yet it was not until this past summer that the company announced it had used the method in a practical application by encrypting the data on a prototype storage drive. Although NIST may not ultimately select CRYSTALS as its new standardized cryptography technique, IBM still hopes to use the system for its own products. Its summer announcement, presented at the Second PQC Standardization Conference at the University of California, Santa Barbara, also included the news of a CRYSTALS modification that should let it encrypt cloud-based data. IBM hopes to use this improvement to render the IBM Cloud quantum-proof by 2020.

Because IBM has also made the system open-source, Lyubashevsky points out, any people interested in protecting their data can try it. "If they really do need their data to be secure 20 years from now, there really are some good options available for the cryptography that they can use," he says.

SPECIAL REPORT

The Crystal Kings

Two researchers in Japan supply the world's physicists with a gem that has accelerated graphene's electronics boom

By Mark Zastrow

Takashi Taniguchi with his crystal-making hydraulic press at the National Institute of Materials Science in Tsukuba, Japan.

MARK ZASTROW

Mark Zastrow is a writer based in Seoul.

THE SMELL OF ACRID METAL FILLS THE AIR AS Takashi Taniguchi reaches into the core of one of the world's most powerful hydraulic presses. This seven-meter-tall machine can squeeze carbon into diamonds—but they aren't on its menu today. Instead Taniguchi and his colleague Kenji Watanabe are using it to grow some of the most desired gems in the world of physics.

For the past eight days, two steel anvils have been crushing a powdery mix of compounds inside the press at temperatures of more than 1,500 degrees Celsius and up to 40,000 times atmospheric pressure. Now Taniguchi has opened the machine, and cooling water is dribbling from its innards. He plucks out the dripping prize, a seven-centimeter-wide cylinder, and starts chipping at its outer layers with a knife to get rid of the waste metal that had helped to regulate the pressures and temperatures. "The last steps are like cooking," he says, focusing intently on his tools.

Eventually, he reveals a molybdenum capsule not much bigger than a thimble. He puts it in a vice and grasps it with a wrench the size of his forearm. With one twist, the capsule fractures and releases a burst of excess powder into the air. Still embedded inside the capsule are glimmering, clear, millimeter-sized crystals known as hexagonal boron nitride (hBN).

Materials laboratories all over the world want what Taniguchi and Watanabe are making here at the Extreme Technology Laboratory, a building on the leafy campus of the National Institute of Materials Science (NIMS) in Tsukuba, outside Tokyo. For the past decade, the Japanese pair have been the world's premier creators and suppliers of ultrapure hBN, which they post to hundreds of research groups at no charge.

They've sacrificed much of their own research and almost all their press's running time to this task. But in doing so, they have accelerated one of the most exciting research fields in materials science: the study of electronic behavior in 2-D materials such as graphene, single-atom-thick sheets of carbon. These systems are thrilling physicists with fundamental insights into some of the quantum world's most exotic electronic effects and might one day lead to applications in quantum computing and superconductivity—electricity conducted without resistance.

It's easy to make graphene itself, by using sticky tape to flake carbon layers from pencil lead (graphite). But to study the complex electronic properties of this material, researchers need to place it on an exceptional surface—a perfectly flat, protective support that won't interfere with graphene's fast-traveling electrons. That's where hBN comes in as a transparent underlayer, or substrate. "As far as we've investigated, that is the most ideal substrate for hosting graphene or other 2-D devices," says Cory Dean, a condensed-matter physicist at Columbia University, who was part of the team that first worked out how to pair hBN and graphene. "It just protects graphene from the environment in a beautiful way."

When a flake of hBN comes into contact with graphene, it can also act like cling film, making it possible to precisely pull up the carbon sheet and place it back down. That allows researchers to create devices by stacking multiple layers of 2-D materials, like a sandwich.

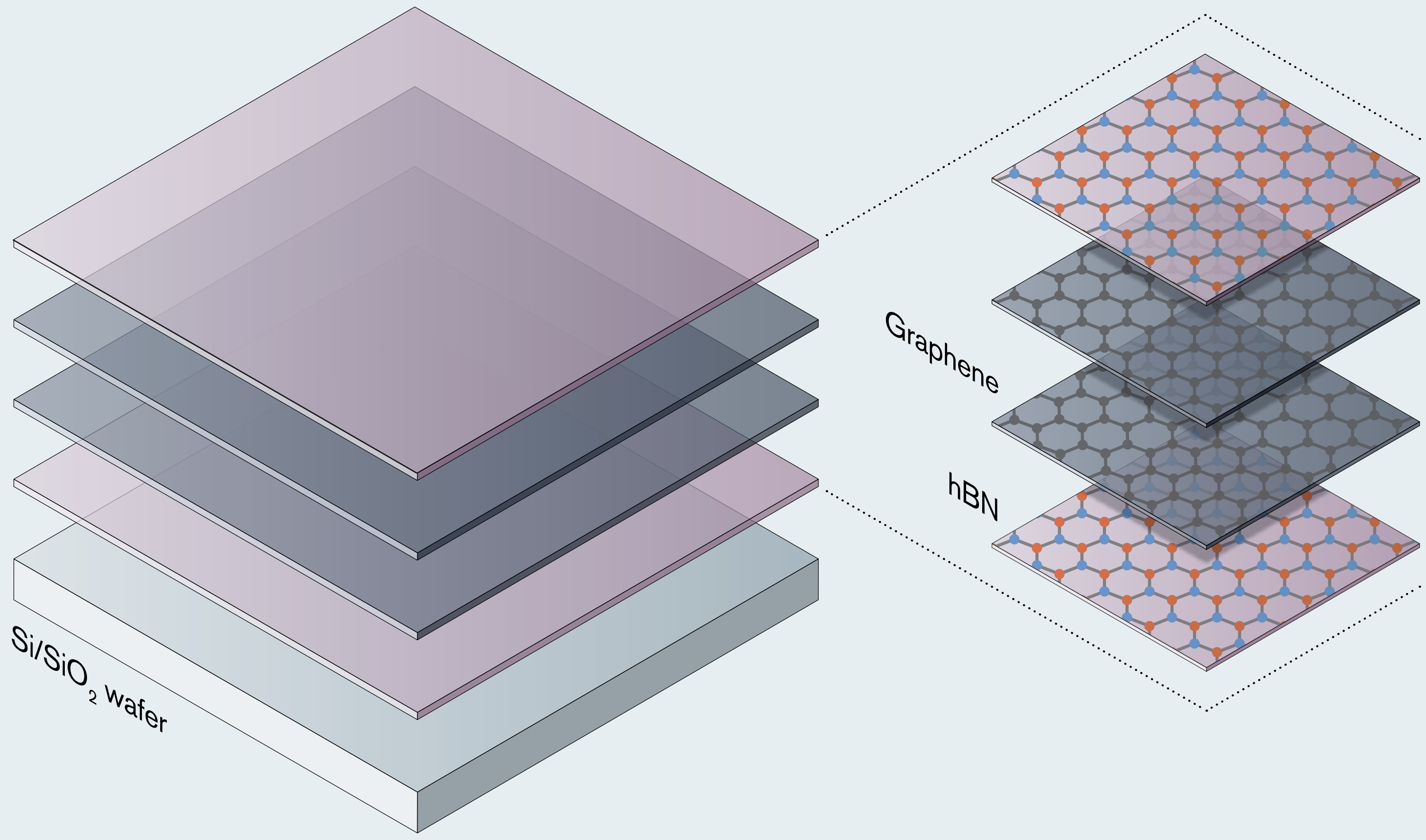
Since 2018, for instance, materials scientists have been buzzing about the finding that simply by misaligning two sheets of graphene by precisely 1.1°—a "magic angle"—the material can become a superconductor at very low temperatures. And last July researchers reported signs of superconductivity when three sheets of graphene are stacked atop one another—no twisting needed. These research studies, like hundreds of others, all used slivers of Taniguchi and Watanabe's hBN to protect their samples. "We are just involved," Taniguchi says modestly. "It is a sort of by-product for us." Dean is more effusive about the pair's hBN: "It's really the unsung hero of the process," he says. "It's everywhere."

Neither Taniguchi nor Watanabe is a graphene researcher, and the scientists had no idea that their gems would become so desirable. They now have several patents related to their hBN-making process but say they don't expect to be able to commercialize it—at the moment, only research groups need the highest-purity crystals. There is a sizable perk, however. Because the pair are credited with authorship on studies using their crystals, they have become among the world's most-published researchers. Together Taniguchi and Watanabe appeared as authors on 180 papers in 2018—and since 2011 they have co-wrote 52 papers in *Science* and *Nature*, making them the most prolific researchers in these journals over the past eight years.

Their crystal empire might not last forever: Taniguchi is edging toward retirement age, and other research groups are trying to make high-quality hBN, which could help improve the supply and speed up research. But for now, physicists are somewhat reluctant to test unproven samples when they know the NIMS ones work so well, says Philip Kim, a leading condensed-matter physicist at Harvard University. "Why Watanabe and Taniguchi? Because their crystal is the best."

Graphene Sandwich

Graphene researchers wrap their materials in flat layers of hexagonal boron nitride (hBN). (Note this is a simplified diagram: equipment to control and measure electric fields in graphene is not shown.)



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UNDER PRESSURE

The massive hydraulic press lives in a cavernous industrial space at the Tsukuba laboratory, which is filled with the continuous hum of machinery and light that streams in from high windows, casting dusty rays across the equipment below. The machine was built between 1982 and 1984, when the lab was a part of the National Institute for Research in Inorganic Materials (NIRIM), one of NIMS's forerunners. Taniguchi arrived five years later, after leaving a postdoctoral position at the Tokyo Institute of Technology. The press was originally designed to make diamonds, but in the 1990s Japan's government embarked on a research program dubbed "Beyond Diamond" to find the next big thing in ultrahard materials, potentially for cutting substances or for use in semiconductors.

One of the program's leading candidates was boron nitride in its cubic crystal form (cBN)—a dense structure in which boron and nitrogen atoms are arrayed like the carbon atoms in diamond. Taniguchi initially focused on growing ultrapure cBN in the press—but his group couldn't eliminate impurities, stray bits of carbon and oxygen that intruded when the samples were being prepared, and so the crystals came out with an unwanted dull, brownish cast. As a by-product, however, the process produced clear hBN, in which layers of hexagonally arrayed atoms slide easily over one another, analogous to the carbon layers in graphite.

Watanabe, a materials scientist and spectroscopist, joined NIRIM in 1994, just as the Beyond Diamond program was starting. He spent a few years studying the optical properties of diamonds. But amid an institute-wide push for cross-disciplinary collaboration in 2001, Taniguchi knocked on Watanabe's door and invited him to take a look at his cBN crystals.

The two researchers have contrasting styles. Taniguchi is known for his parties, blasts the music of Queen through the lab as he runs the press late at night and, even at the age of 60, still plays soccer with his colleagues at lunchtime. Watanabe, three years younger, is soft-spoken, detail-oriented and prefers tennis. But the scientists worked well together and published their first paper on cBN crystals in 2002.

A year later Watanabe, complaining about the quality of the cBN that Taniguchi was passing to him, took a look at a box of discards from the press. The hBN crystals caught his attention, and he decided to examine their properties. Taniguchi was skeptical: "I said, 'This is hBN—the boring stuff!'" Watanabe, however, discovered something new: the hBN luminesced under ultraviolet light—unlike the diamond or cBN that he had been looking at for years. "It was the most exciting moment of my career," he says—a finding that left him buzzing for weeks afterward. The pair reported that result in May 2004, proposing that hBN could be a promising crystal for UV lasers.

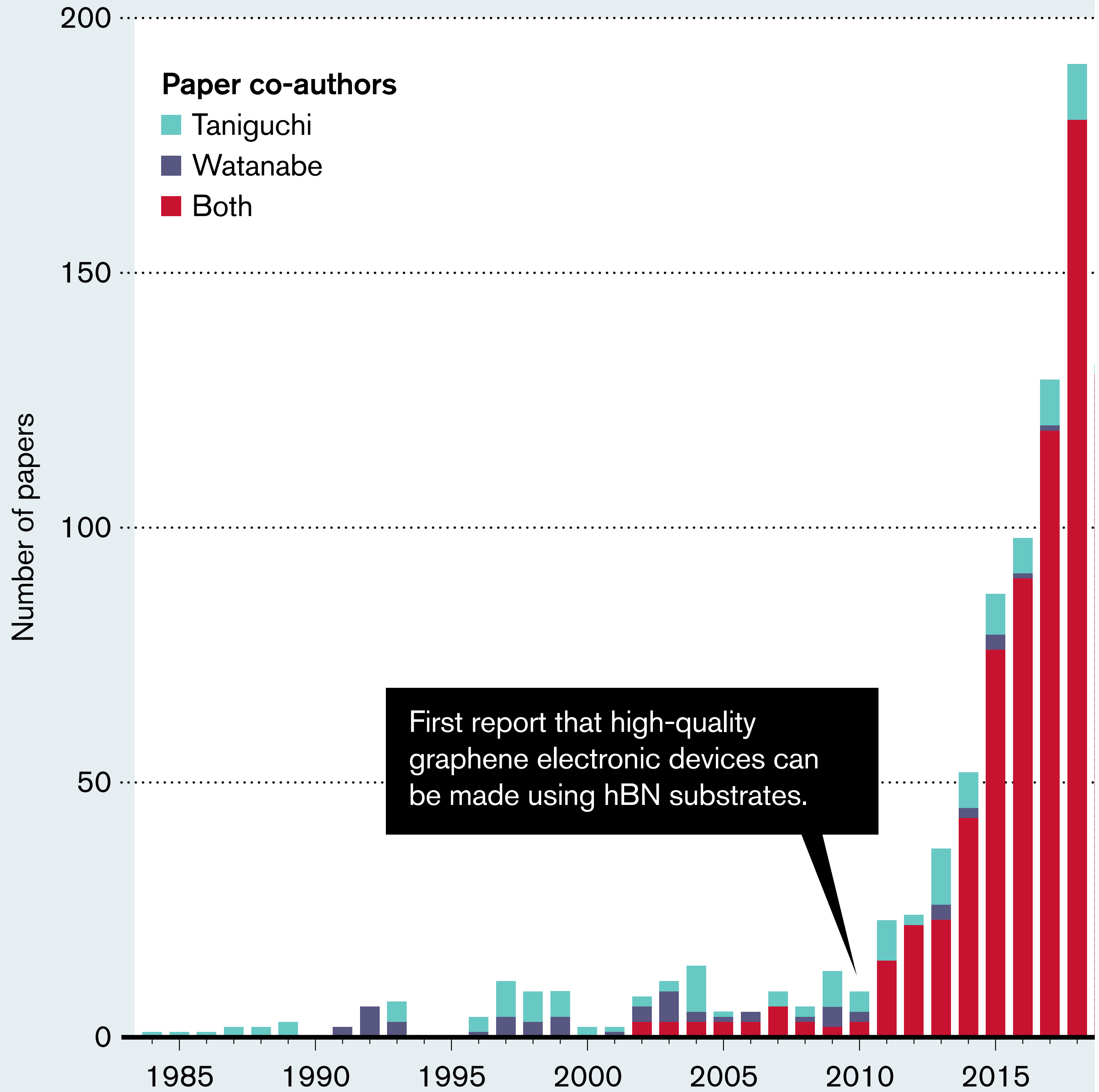
Later that year a preprint began circulating from physicist Andre Geim and his team at the University of Manchester, U.K. They had successfully isolated single-atom layers of graphene, kicking off the craze for atomically thin 2-D materials. The frenzy of activity was something Taniguchi and Watanabe observed with curiosity. "We had no idea about 2-D materials," Taniguchi says. But half a decade later 2-D materials researchers would find out about them.

AN EYE-POPPING DISCOVERY

In 2009 the graphene field was running into a problem. In theory, the material was remarkable, but researchers were struggling to realize its full potential. The problem seemed to be that graphene, being a single atom thick, conforms to the shape of whatever surface it is placed on. The flatness that makes the material unique is lost if this substrate is not equally flat. Also,

Crystals in Demand

Takashi Taniguchi and Kenji Watanabe have co-authored hundreds of papers by supplying crystals of hexagonal boron nitride (hBN) to physics laboratories around the world.



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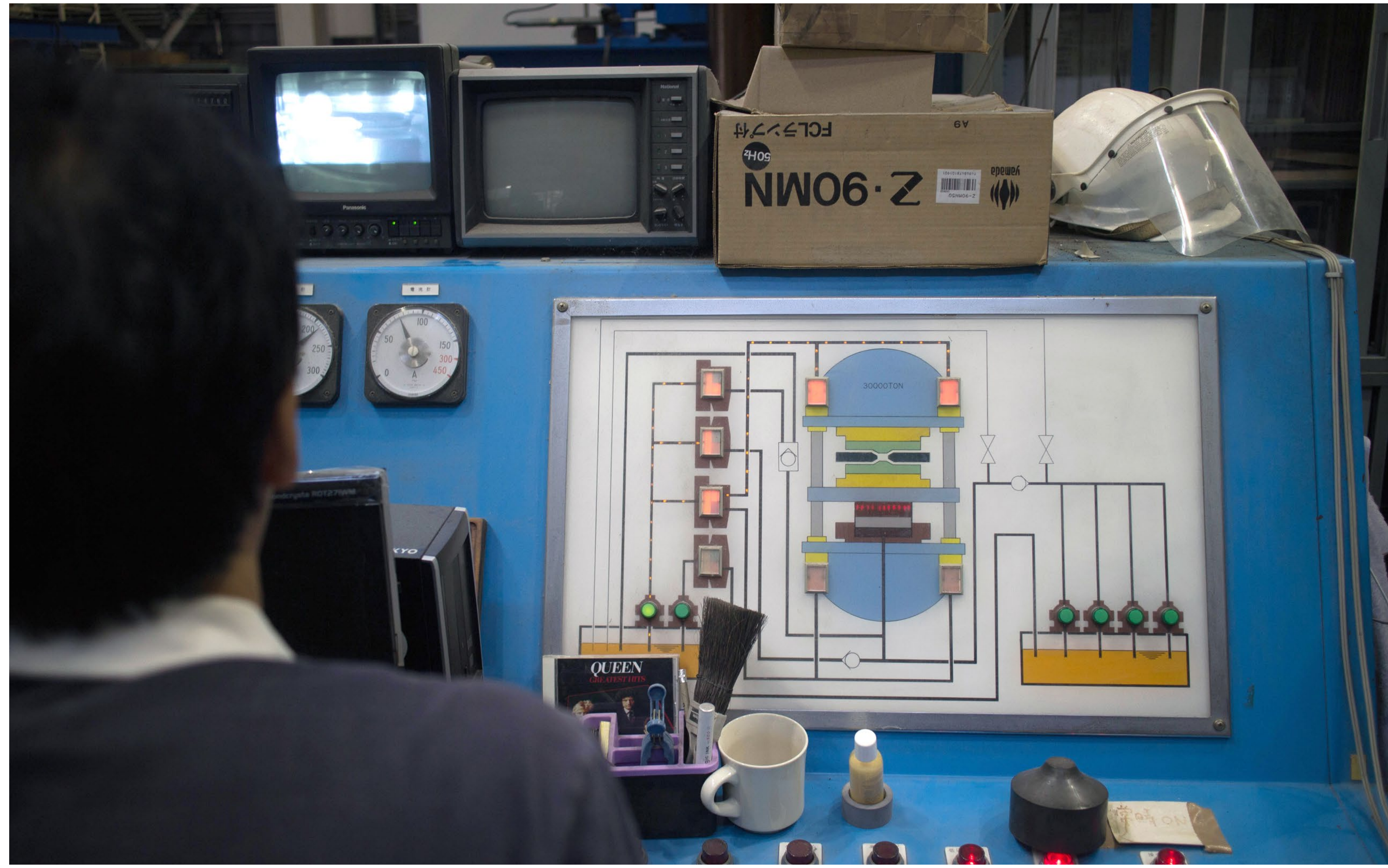
because graphene is so thin, electrons traveling through it are, essentially, in contact with the substrate it rests on. That means the substrate needs to be incredibly pure: any impurities will cause the electrons to scatter, reducing electron mobility. The standard silicon oxide substrates weren't good enough and seemed to be limiting graphene's performance.

James Hone, a mechanical engineer at Columbia University, and his then postdoc Cory Dean had a better substrate in mind: hBN. It is atomically flat, plus it has a wide bandgap—that is, a large energy barrier that prevents electrons bound to atoms from jumping into a mobile, conductive state. That makes hBN a good insulator.

By chance, another of Hone's postdocs, Changgu Lee, had some experience with the stuff. He was studying the mechanical and electrical properties of 2-D materials and had already sourced hBN samples from a commercial firm that made hBN for the cosmetics industry; some eyeliners are up to 25 percent boron nitride. One day, as the three sat outside the department building eating sandwiches, Hone suggested that Lee give Dean some of his hBN so that Dean could try using it as a graphene substrate. Lee was happy to but added that he had read in the literature about a potentially higher-quality option: the larger, purer hBN crystals produced at NIMS by Taniguchi and Watanabe. There was just one problem: he'd contacted them before, but communications had dried up. Hone suggested asking Philip Kim—"the most famous guy in graphene," as Lee says, and a faculty member at Columbia at the time—to write a request for them.

This worked, and Kim, Lee and Dean became the first outside users of the NIMS crystals for graphene research. It took Dean a year, collaborating with Ph.D. students Andrea Young and Inanc Meric, to work out how to consistently maneuver graphene and hBN flakes into contact with each other. But the results were stunning. Resting on the NIMS hBN samples, the graphene's roughness



Taniguchi at the controls of his hydraulic press—with the Queen CD that he plays in the lab.

MARK ZASTROW

was reduced by two thirds when compared with graphene on a silicon oxide substrate—and the electron mobility was 10 to 100 times better.

The team members presented their findings at the annual Graphene Week conference in April 2010 at the University of Maryland in College Park—and "everybody's eyes popped," Kim says. "It was a sensation." Instantly, everyone wanted to know how to get the hBN—including Geim, who shared the Nobel Prize for Physics that year for his work on graphene. He e-mailed Kim with one question: "Philip: What is the source?"

Taniguchi and Watanabe were suddenly inundated with inquiries and requests for samples. But when Geim, a competitor to Kim, asked them, they hesitated to reply. "Things could have become complicated," Taniguchi says. "We made the crystal—they found the property." He asked Kim: Would it be okay to supply other groups—including their direct competitors? "Of course," Kim said. "A small research group at Columbia should not monopolize your crystal," Taniguchi recalls him saying.

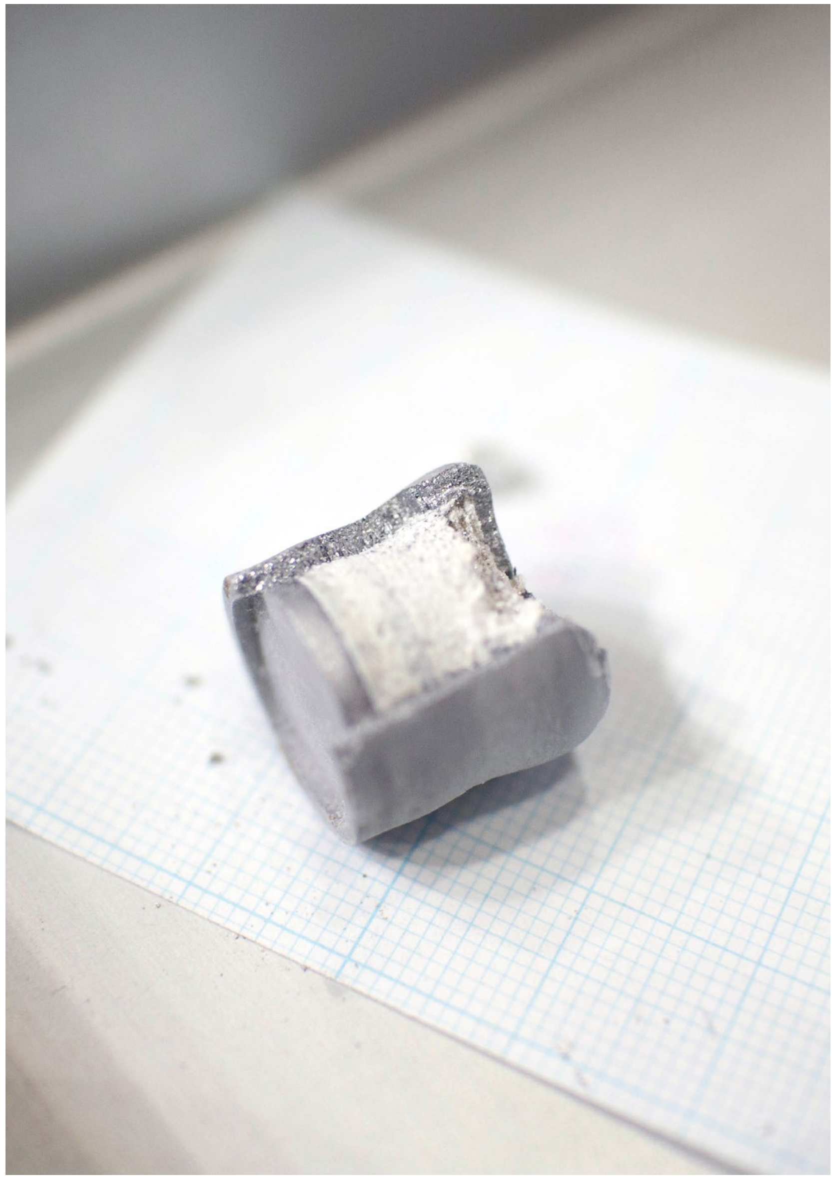
COLLABORATION ALL AROUND

Today Taniguchi and Watanabe have agreements to supply more than 210 institutions around the world. Taniguchi preps the crystals for posting in an office on the perimeter of the lab, where stacks of clear plastic trays holding batches of samples are scattered around microscopes on a counter. Taniguchi's current batch is number 942—the latest in his records, which go back over a decade. The total weight of crystals in each package—holding four different samples from four runs of the press—is roughly one gram. But that can keep an entire research group going for a year.

Taniguchi and Watanabe don't explicitly ask to be full co-authors on papers, they say. To receive the samples, users sign a materials-transfer agreement with NIMS. Many researchers say the pair's co-authorship status reflects the importance of sample growers in the field. "Without their samples, without their involvement, I don't think that what we are doing can be done at this point, so sharing the authorships is really well deserved," Kim says.

The worst part of the supply operation is the paperwork, Watanabe says: "It's a hard burden—very heavy." Authors at NIMS have to file individual reports with their supervisors when they submit a paper, when it's accepted and when it's published. Watanabe, the junior partner and the more detail-oriented of the two, takes on the task. He uses an app on his laptop to keep track of the pair's articles and preprints, which now number more than 700.

In most studies, Taniguchi and Watanabe's interaction is limited to supplying the crystals and, they hope, getting feedback from those groups on the crystal quality. Not everyone takes the time to write back, says Taniguchi, to his disappointment. But their work with the members of the original Columbia group—and the second-generation groups that the former Columbia students launched when they established their own labs elsewhere—remains a true collaboration. "They have been phenomenal partners in this process," Dean says. "They've worked with us not only to provide boron nitride but also to try to figure out how to make things cleaner and make a variety of things that are interesting to us."



The synthesized hBN crystals, together with uncrystallized boron nitride powder, are contained in a molybdenum capsule.

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After the 2010 Graphene Week presentation, for instance, a postdoctoral researcher in Kim's lab named Pablo Jarillo-Herrero was the first person to ask the Japanese pair for crystals. He now leads the team at the Massachusetts Institute of Technology that reported superconductivity last year in twisted double layers of graphene—a configuration protected by two layers of Taniguchi and Watanabe's hBN. And when physicist Rebeca Ribeiro-Palau moved from Dean's group in 2017 to lead her own team at the Center for Nanoscience and Nanotechnology in Palaiseau, France, she immediately got in touch with the Japanese pair. "Making a collaboration with them was the first step, before even opening the lab," she says.

Graphene isn't the only 2-D material to benefit from hBN, Ribeiro-Palau adds. Layers of more complex materials called transition-metal dichalcogenides, for example, have also been stacked and twisted to modify their electronic properties, something that again requires hBN. "It's exactly what you need to encapsulate the materials, to protect them, to give different properties, to change the spacing between layers. We use boron nitride for almost everything," Ribeiro-Palau says.

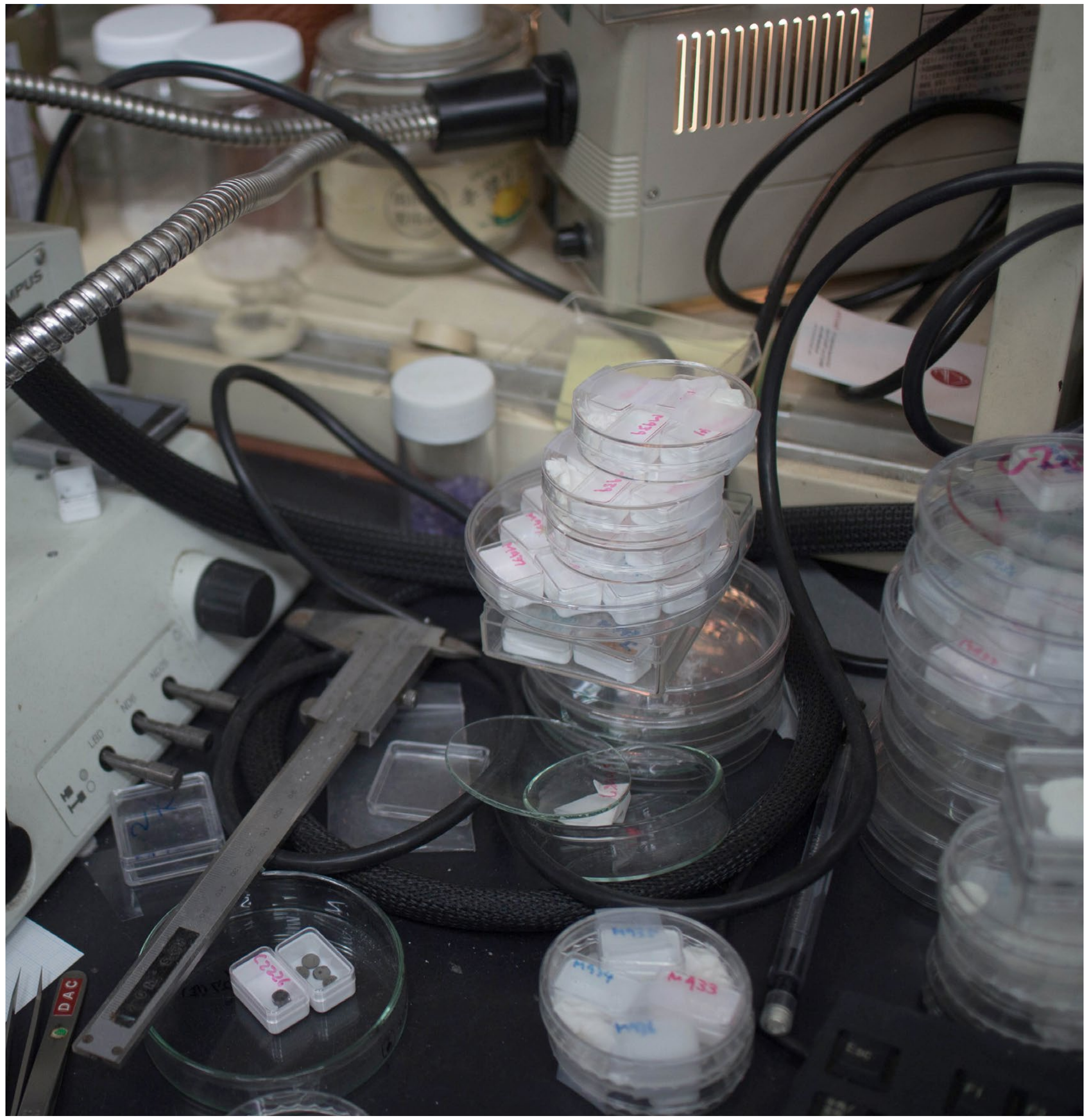
There are increasing hints that hBN can take on more than a supporting role in such devices. Aligning hBN's hexagonal structure with one of the layers in twisted graphene can break the symmetry of the graphene sheets, altering the way electrons interact, according to separate preprints reported in 2019 from teams led, respectively, by David Goldhaber-Gordon of Stanford University and Andrea Young, now at the University of California, Santa Barbara.

Hexagonal boron nitride is also becoming recognized as a fascinating 2-D material in its own right. Bathed in infrared light, hBN acts as a hyperlens: it can focus light and create images sharper than classical physics allows. And it has potential as a material that can emit single photons—a useful function for quantum cryptography. Watanabe's finding that the material could be useful as a UV laser still receives attention, and his primary research goal remains working out how this happens.

Some of this work is done using hBN grown by methods that produce lower-quality samples, such as depositing the crystal in a thin film from a chemical vapor, which doesn't require high pressures. But for graphene researchers, Taniguchi and Watanabe's crystals remain the ones of choice. "Over the years we tried four or five other sources of hBN, and they were all rubbish," Geim says. With high-purity hBN in short supply, that hinders progress in global graphene research, he says.

Other teams are starting to catch up. A group led by chemical engineer James Edgar of Kansas State University in Manhattan has now come close to achieving the quality needed to rival Taniguchi and Watanabe's process, Geim notes. Edgar says it's not easy to duplicate the Japanese team's work, because they have an expensive, giant press. But his samples, made by a simpler—and much cheaper—process involving a furnace fed with boron nitride and a nickel-chromium solvent in powder form, are "as good or nearly as good" for graphene research purposes, he says. Currently, however, they have 10 times more crystal defects, or imperfections, in their structure.

Taniguchi, for his part, relishes the prospect of challengers to their crown, and the chance to push each other to grow purer and more perfect crystals. "We're fighting to improve our systems," he says, "but we need many collaborators—and also competitors."



Kenji Watanabe prepares hexagonal boron nitride (hBN) crystals (*left*); stacks of plastic trays holding hBN pile up for posting around the world.

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A CAREER GROWING CRYSTALS

Last July, Taniguchi turned 60—the age at which researchers retire at NIMS. That was a concern for Kim. "I told him, 'Hey, Takashi, the entire 2-D research field is in danger now. So we should do something!'" Luckily for the 2-D field, NIMS granted Taniguchi a reprieve: earlier in 2019 they promoted him to a fellow position, which allows him to work until 65. He hasn't developed a succession plan yet or identified a protégé.

For now, he continues to run the press alone. Back in his lab, he prepares the next batch—number 943—filling a fresh thimble-sized capsule with white disks of boron nitride the size of breath mints. In between, he places a layer of barium nitride and other barium compounds, which dissolve along with the boron nitride and act as a solvent and catalyst to aid the crystal's growth and absorb impurities.

Taniguchi is cagey about the exact recipe: this is his secret sauce, and he likes to change the composition of the barium layer from batch to batch. "Using the same recipe every time is not that fun," he says. For first-time users, he'll send some baseline crystals, but with long-time users, he wants feedback on each slight change to the process. By measuring electron mobility in graphene, they can detect impurities in the underlying hBN with more sensitivity than Taniguchi and Watanabe can measure. At first, no one had any complaints about their crystals. Only in the past two years, Taniguchi says, have researchers begun reporting impurities that affect their results—a result of them pushing the limits of the material. And that motivates Taniguchi to improve. "I'm a crystal grower," he says proudly.

He clambers up over the press platform, crouching down in the jaws of the machine to place the new capsule. Back to the controls: a few button presses, and the lower anvil begins rising from the floor to hit the core. As a red digital readout counts down the distance, Taniguchi wipes some grime off the console with a tissue.

Despite decades of work growing crystals in the press, there is still much to uncover about the fundamental physics of how the process works, he says. What actually happens inside that capsule when the press clamps down remains a mystery. "Nobody knows how to measure it, how to think about what's happening, how the crystal grows. It's just imagination."

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Sophie Evans graduated from Princeton University in 2019 with a degree in Near Eastern Studies and a certificate in Humanistic Studies.

GETTY IMAGES

OBSERVATIONS

How Mere Humans Manage to Comprehend the Vastness of the Universe

Peering into the unknown requires us to recognize our own mental blind spots

Astrophysics is not typically considered to be part of the humanities. Yet one class I took as a senior at university suggested otherwise. It left me in awe of the human mind.

With my background rooted in the humanities, I found myself focusing on the way my professors described the cosmos. While the fantastical environments of black holes, white dwarfs and dark matter often took center stage, at the heart of each discovery was the human mind seeking to understand the unfamiliar.

Their tales of discovery made it clear that we often take our knowledge of the universe for granted. After all, the universe was not built for the human mind to understand. When we look up at the night sky, we see only a tiny fraction of what is out there. It is the task of the astrophysicist to develop a picture of the universe despite our overwhelming blindness.

I wanted to better understand how being human shapes our understanding of the universe. After talking to some of Princeton's leading astrophysicists, one thing became clear: the discipline requires the human mind to be conscious not only of the universe but of itself (unless otherwise identified, all quotes are from these scientists).

Only 5 percent of the universe is normal, observable matter. Within this small fraction, the human eye can only perceive matter that emits light within a certain frequency on the electromagnetic spectrum. While birds can perceive magnetic fields and snakes can image in the infrared, we can detect only visible light. This range determines our picture of space, Adam Burrows explains. Our picture of space is, in that sense, a direct product of the human mind.

Rather than assuming our picture wholly captured the universe, Jo Dunkley says astrophysicists "started wondering whether there might be other things filling our galaxies and universe that we cannot see." They designed telescopes to detect frequencies of light that lie beyond human perception, such as those of x-rays and radio waves. With these instruments, our picture of the universe became 5 percent complete.

The astrophysicists' task then became one of using the visible to detect the remaining 95 percent. Einstein's laws of gravity provided a means of navigating the obscure. Because gravity depends solely on mass, its effects can be seen irrespective of light production. As Dunkley explains, a massive, invisible object, such as a black hole, will attract a visible object, like a star.

While the Event Horizon Telescope's image of a black hole is one recent example, the strategy dates back as early as 1933. It was Swiss astronomer Fritz Zwicky who unwittingly first employed the technique when examining the behavior of galaxy clusters. He found the clusters to be far more massive than anticipated based on what was visible. He called the missing mass "dark matter." Nearly 40 years later American astronomer Vera Rubin confirmed its existence. While measuring the radial velocity of galaxies, she observed velocities incompatible with those predicted by the laws of gravity. The expectation had been that objects farther from the center of the galaxy orbited more slowly than those near the center. Rubin instead observed a constant velocity, meaning that there was no decrease at the fringe of the galaxies. In order for this to be possible within the laws of physics, there must be "more to space than meets the eye," Dunkley explains. The mass existed—it just had yet to be detected.

Neta Bahcall explains that it's the laws of gravity that render this dark matter indirectly observable. They allow astrophysicists to determine how much of the universe is invisible without knowing exactly what the darkness is. James Jeans once likened the situation to Plato's well-known allegory, where "imprisoned in our cave, with our backs to the light, we can only watch the shadows on the wall." The comparison is apt. Counterintuitively, the "shadows" here represent what is visible, and the "light" represents what we cannot see or even imagine. With this technique, dark matter came to contribute 27 percent to our cave drawing of the universe.

The 68 percent of the universe absent from our drawing is still unknown. But, in 1998, that unknown was given a name: dark energy. It emerged as a means of explaining the universe's anomalous expansion. In the 1990s astrophysicists thought that the universe's rate of expansion would gradually decrease. The laws of gravity predicted that the matter filling the universe would begin to pull itself together as time went on, thus slowing the universe's expansion. Yet this turned out not to be the case. The expansion was accelerating. Very little is known about dark energy, and so our picture of the universe remains far from complete.

The problems facing our picture of the universe are not limited to what we can perceive. As Ed Turner explains, "our mind and the culture in which it was formed condition the way we explore the universe." Because of this particular conditioning, we have mental blind spots for the cosmic phenomena that run counter to human intuition and understanding. For instance, Turner claims that the mind is "predisposed to see things as statistically significant when they might not be." We erroneously perceive patterns in the spacing of stars and of the planets in the solar system, seeing them as though they were arranged.

There are other "properties of the mind that get in the way of seeing the truth," according to Turner. Consider, for instance, our belief that massive objects must take up space. It is not a direct relationship: we accept that a piece of lead is more massive than a pillow, even though the latter is larger. At the extremes, however, we expect some positive correlation between the two. The extreme physical environment of a neutron star then poses problems. As Michael Strauss suggests, the star is so dense that "a thimbleful of neutron star material has the mass of 70 million elephants." We cannot help but wonder: Where is all the mass?

We are "blinded by being human when we look at something larger than the human experience," Robert Lupton explains. It becomes further apparent when we are confronted with counterintuitive phenomena such as white dwarfs and black holes. White dwarfs decrease in size as they become more massive, says Joshua Winn, and for black holes, all mass is compressed to zero size. While we cannot see the black hole, giving the phenomenon a name allows us to imagine it. The same could be said of dark matter and dark energy, Dunkley explains. As with the previous analogy, language provides a means of overcoming our initial blindness to interact with these cosmic phenomena.

Astrophysicists encounter another blinding property of the mind when considering the nature of space: we can only visualize in three dimensions. In order to imagine the geometry of space—namely, whether it is flat or curved—we would need to be able to think in four dimensions, Dunkley says. For instance, to determine the curvature of a ball, we first picture the ball in three dimensions. Therefore, to determine a three-dimensional curve, the mind would need to picture the four-dimensional object.

This need arises when astrophysicists contemplate the expanding universe and relativity. For the former, the task is to conceptualize a three-dimensional universe that exists in a loop—an impossible visualization, for connecting every dimension would create a four-dimensional object. For the latter, in order to explore the relativistic behavior of spacetime, the task is to imagine a three-dimensional space deformed by gravity—another impossibility.

In both cases, two-dimensional analogies facilitate understanding. Dunkley likens the universe to a piece of string attached at both ends to create a loop and then relies on language to bridge the dimensional gap. We would connect every side of space, such that no matter the direction we traveled in, we would always return to our starting point, she explains. Similarly, in his 1915 paper on general relativity, Einstein used a trampoline as a two-dimensional analogue for space. He then turned to language to illustrate how placing a massive object on the stretchy surface creates a third, vertical dimension. The same principle applied in more dimensions, he argued: massive objects bend space. While we are still unable to visualize the four-dimensional phenomena, Dunkley says that through these linguistic analogies, "we can imagine the consequences."

In this manner, astrophysicists "stretch the mind to see the universe from an external perspective," Turner says. Burrows speaks of retraining the brain by developing a new language better suited for the "conversation between the cosmos and the individual." The environment of the universe is so different from our daily environment that often we cannot imagine it, according to Joel Hartman. Take, for instance, the size of the universe and the number of stars within it. The language of mathematics, grounded in scientific notation, logarithms and orders of magnitude, allows us to grapple with the cosmos where words fall short, Burrows explains.

Similarly, when considering the four-dimensional universe, mathematical measurements provide astrophysicists with an invaluable means of navigating the obscure. "Just like in two dimensions," Dunkley notes, "if the geometry of space is flat, then parallel lines, like light rays, stay parallel always. If the space is curved, then they will either come toward each other in a positively curved universe or splay apart in a negatively curved one." To return to the language of Plato's cave, it seems that by measuring the shadows before us, we are able to conceptualize, in part, the nature of what remains out of sight and out of mind.

Even with this universal language of mathematics, astrophysicists still resort to biological terms to describe certain cosmic phenomena. Turner describes how astrophysicists speak of the birth and death of stars, as though they were alive. More extreme is the "twin paradox" devised to facilitate a correct conception of time. We are accustomed to thinking of time as strictly linear and independent, but Einstein's theory of relativity says that probably is not the case. Time passes more slowly when close to massive objects.

To overcome our intuition, astrophysicists imagine "taking two twins and somehow sending one of them to spend time near a black hole, [so that] she would actually age more slowly than [her] Earth-dwelling partner," Dunkley says. The physical manifestation of aging allows the mind to grapple with the nonuniformity of time, for we are able to envision two differently aged twins despite the semblance of a paradox.

While there are certainly "properties of the mind that get in the way of seeing the truth," as Turner says, the fact that it is human allows us to engage with the universe. The lives of stars and the twin paradox are just two examples of astrophysicists making sense of the unfamiliar through our own biology. After all, it is the mind of the astrophysicist that must first identify its blind spots and then devise techniques to overcome them. In that sense, astrophysics and humanism go together in a wonderfully unexpected way. As literary critic Leo Spitzer once wrote, "The humanist believes in the power of the human mind of investigating the human mind."

So often the predominant reaction to astrophysics focuses on how vast the universe is and how insignificant a place we hold in it. It would be far better to flip the narrative to see the marvel of the mind exploring the cosmos, human lens and all.

Christian Zur is executive director of the U.S. Chamber of Commerce Procurement and Space Industry Council.

SPACE

The International Space Station Is More Valuable Than Many People Realize

It's crucial to our exploration of the solar system, but this marvel of innovation has not always had the support it deserves

GETTY IMAGES

In 1984 when President Ronald Reagan directed NASA to build a permanently occupied space station, no one could have predicted the critical role it would play in human space exploration nearly four decades later.

The International Space Station (ISS) took 12 years to build with support from 16 nations and has been populated continuously since November 2000. A colossal achievement by any measure—the station weighs a million pounds and is the single most expensive object ever built. And it should be.

Truly a jewel in the crown of human achievement, the ISS gave the U.S. and its partners an operational outpost in the most austere environment ever known.

Over its life span, more than 2,400 experiments have been conducted by more than 230 visitors from 18 countries. The station's crew have logged over 1,300 extravehicular activity (EVA) hours on more than 217 space walks. Over their lifetime, teenagers have seen a constant revolution in technology, some of it exclusively the result of space access and research.

But this marvel of innovation has not always had the support it deserves.

Since the high point of the Apollo program, NASA endured criticism for being too focused on sustaining the space shuttle at the expense of deep-space exploration. Not surprisingly, political support and funding atrophied as a result. Indeed, in 1993 the station came a mere one vote away from termination in the House of Representatives.

And yet, while few were watching since the shuttle stood down in 2011, a new and reinvigorated agency is emerging with a vision that should captivate even the cynics. Under Space Policy Directive 1 (SPD-1), NASA and the ISS National Laboratory are accelerating the nation's push into commercial space. With an expected $1-trillion space economy to come, the ISS can play a defining role in the formation of the industry.

Onboard the ISS, an array of basic and applied research programs are underway with participation of companies such as Boeing, Anheuer-Busch, Sanofi, LambdaVision, Space Tango, Airbus and Teledyne Brown Engineering. The ISS is effectively the premier space R&D lab, and companies are utilizing microgravity at the edge of the human frontier 250 miles up to solve problems here on Earth.

Beyond the major policy shift announced last June to allow for greater commercial partnerships onboard the ISS, other major milestones are underway. Last July, NASA and Boeing assembled 80 percent of the massive core stage needed to launch the Space Launch System and Orion on their first mission to the moon: Artemis 1.

Notably, NASA's "new" charge to facilitate and encourage the commercial sector is nothing new. After all, NASA has fostered some of the greatest technological developments in all of human history. And late in 2019 NASA's Commercial Crew transport was set to launch from Cape Canaveral to resupply the ISS.

But no one should take for granted the colossal task of maintaining this orbital toehold. Despite being sheltered within our planet's magnetic shield, the ISS has endured a battering equivalent to an aircraft carrier in World War II's Battle of Midway. Shuttle veteran Alvin Drew recounted to the U.S. Chamber of Commerce a year ago his EVA experience with razor-sharp ISS exterior surfaces because of the sandblasting effect of the low Earth orbit environment.

Just maintaining the operational status of the station alone is an achievement. Over the decades NASA and Boeing, as prime contractor, have stretched and maximized the platform as a test bed to fully evolve our understanding of microgravity's effect on metabolic systems. Humans are fragile after all. But SPD-1 boldly charts out human exploration to the moon, Mars and beyond.

With the ISS as its point of departure, NASA's recently announced Lunar Gateway program will be the platform to prepare and propel humans to Mars. To paraphrase administrator James Bridenstine, Gateway will be the permanent lunar command module.

And in 2024 Gateway will facilitate the mission objective of Artemis 1 to land astronauts near the lunar south pole. But we can't get there from here—not without the ISS. The lion's share of onboard station research is aimed at solving long-term challenges for human survival in deep space. The ISS is the tethered ship from which astronauts will hone spacefaring skills to venture beyond the proverbial horizon.

In this new era of exploration, the ISS is allowing the right questions to be asked and answered. One could say that, to date, we have been consumed with identifying the limitations inherent in humanity's reach into space. Yet recently, we have begun to ask a more nuanced and intriguing question: What are the unique characteristics of the domain beyond Earth that we can use for our benefit?

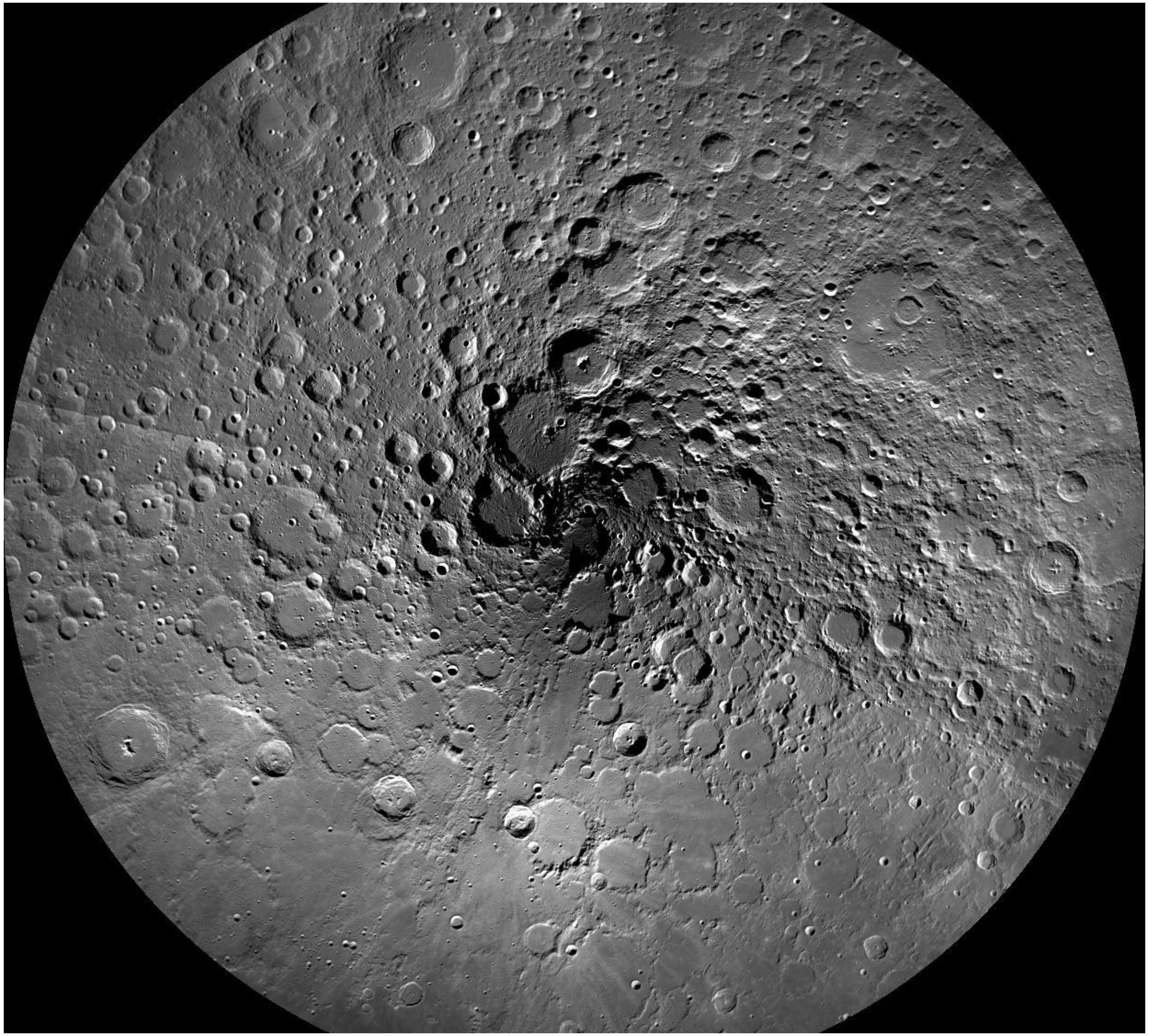
Although the future of deep-space exploration is no more known today than it was in 1984, all that is certain is the ISS will be the launchpad for wherever humans go from here.

Abraham Loeb is chair of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the advisory board for the Breakthrough Starshot project.

SPACE

The Moon as a Fishing Net for Extraterrestrial Life

Its surface could, in principle, preserve the remains of organisms or even technology from beyond our solar system



NASA, GSFC AND ARIZONA STATE UNIVERSITY

NASA recently announced the Artemis lunar exploration program, consolidating its plans to land humans on the moon by 2024 and establish a sustainable base there by 2028. This ambitious initiative revives an old question: Will the unique qualities of the lunar surface enable new frontiers in astronomy?

A few decades ago astronomers had already begun to contemplate different ways their observations could benefit from the absence of an atmosphere on the moon. First, energetic particles such as gamma rays, x-rays, ultraviolet photons or cosmic rays would not be blocked by an atmospheric blanket as they are on Earth, and hence they would reach telescopes with large collecting areas mounted to the lunar surface.

Second, observatories sensitive to optical, infrared, millimeter or radio waves could reach their diffraction limit without the blurring or absorption associated with passage through turbulent air. Arrays of detectors could therefore constitute giant interferometers with unprecedented angular resolution.

Third, the lack of an ionosphere would allow radio observatories to receive signals at very low frequencies, below the terrestrial cutoff of 10 kilohertz. This would open a new spectral window into the universe, allowing to map the three-dimensional distribution of hydrogen atoms from their first appearance 0.4 million year after the big bang and through the cosmic dawn, using the highly redshifted 21-centimeter line. Though exciting and path breaking in their own right, these visions were all formulated well before the emergence of the frontier of astrobiology associated with the search for extraterrestrial life.

Can the moon provide clues for extraterrestrial life? A new paper I wrote with Manasvi Lingam answers this question in the affirmative. The idea is to consider the moon's surface as a fishing net for interstellar objects collected over time and potentially deliver building blocks of life from the habitable environments around other stars.

The lack of a lunar atmosphere guarantees that these messengers would reach the lunar surface without burning up. In addition, the geological inactivity of the moon implies that the record deposited on its surface will be preserved and not mixed with the deep lunar interior. Serving as a natural mailbox, the lunar surface collected all impacting objects during the past few billions of years. Most of this "mail" comes from within the solar system.

But the solar system also intercepts objects from interstellar space, ranging from dust particles to free-floating planets and stars. A detection of the first interstellar object, 'Oumuamua, with a size on the order of 100 meters was reported in 2017. In 2019 'Oumuamua's cousin was tentatively discovered in the form of a meter-size meteor from outside the solar system that burned up in Earth's atmosphere in 2014. And most recently, yet another interstellar visitor may have been identified.

Given the search volume and duration of the surveys that made these detections, it is now possible, for the first time, to calibrate the flux of interstellar objects (assuming they enter the solar system on random trajectories). With this calibration at hand, one can calculate the amount of interstellar material that has collected on the moon's surface over its history. The buildup of interstellar matter can also be observed in real time; another new paper with my undergraduate student, Amir Siraj, showed that a two-meter telescope on a satellite in orbit around the moon can observe interstellar impactors as they crash.

In case some interstellar impactors carry the building blocks of extraterrestrial life, one could extract these biomarkers by analyzing lunar surface samples. Moon rocks delivered to Earth by the Apollo mission were likely contaminated by terrestrial life and are not a viable alternative to a dedicated experimental base on the moon.

Identifying biomarkers from debris of material that originated in the habitable zone around other stars would inform us about the nature of extraterrestrial life. The fundamental question is whether distant life resembles the biochemical structures we find on Earth. Similarities might imply that there exists a unique chemical path for life everywhere or that life was transferred between systems. Either way, a lunar study shortcuts the need to send spacecraft on extremely long missions to visit other star systems.

Getting similar information from a trip to the nearest star system—Alpha Centauri A, B or C—would take nearly nine years round-trip, even if the spacecraft were to travel at the maximum speed allowed in nature, the speed of light; the first half of this period is required for reaching the target and the second half for the information to get back to us. With chemical rockets, this journey would take about 100,000 years, on the order of the time that elapsed since the first modern humans began migrating out of Africa. Excavating the lunar surface for physical evidence of extraterrestrial life is dramatically faster.

Based on the newly calibrated flux of interstellar objects, their debris should constitute up to 30 parts per million of lunar surface material. Extrasolar organics might amount to a fraction of an order of a few parts per 10 million. Amino acids, which serve as the building blocks of "life as we know it," could amount to a few parts per 100 billion. Standard spectroscopic techniques can be employed to examine individual grains within the lunar regolith and search for signatures that would flag them as extrasolar before unraveling the building blocks of extraterrestrial life within them.

How can extrasolar origin be identified? The simplest flag would be a deviation from the unique solar ratio for isotopes of oxygen, carbon or nitrogen. Laboratories have already demonstrated the feasibility of this method at the required sensitivity levels.

But there is also the exciting opportunity for detecting biosignatures of extinct extraterrestrial life. On Earth, the oldest microfossils, with unambiguous evidence for cells that lived about 3.4 billion years ago, were discovered in the Strelley Pool Formation in Western Australia. It would be tantalizing to find microfossils of extraterrestrial forms of life on the moon. Even more exciting would be to find traces of technological equipment that crashed on the lunar surface a billion years ago, amounting to a letter from an alien civilization saying, “We exist.” Without checking our mailbox, we would never know that such a message arrived.

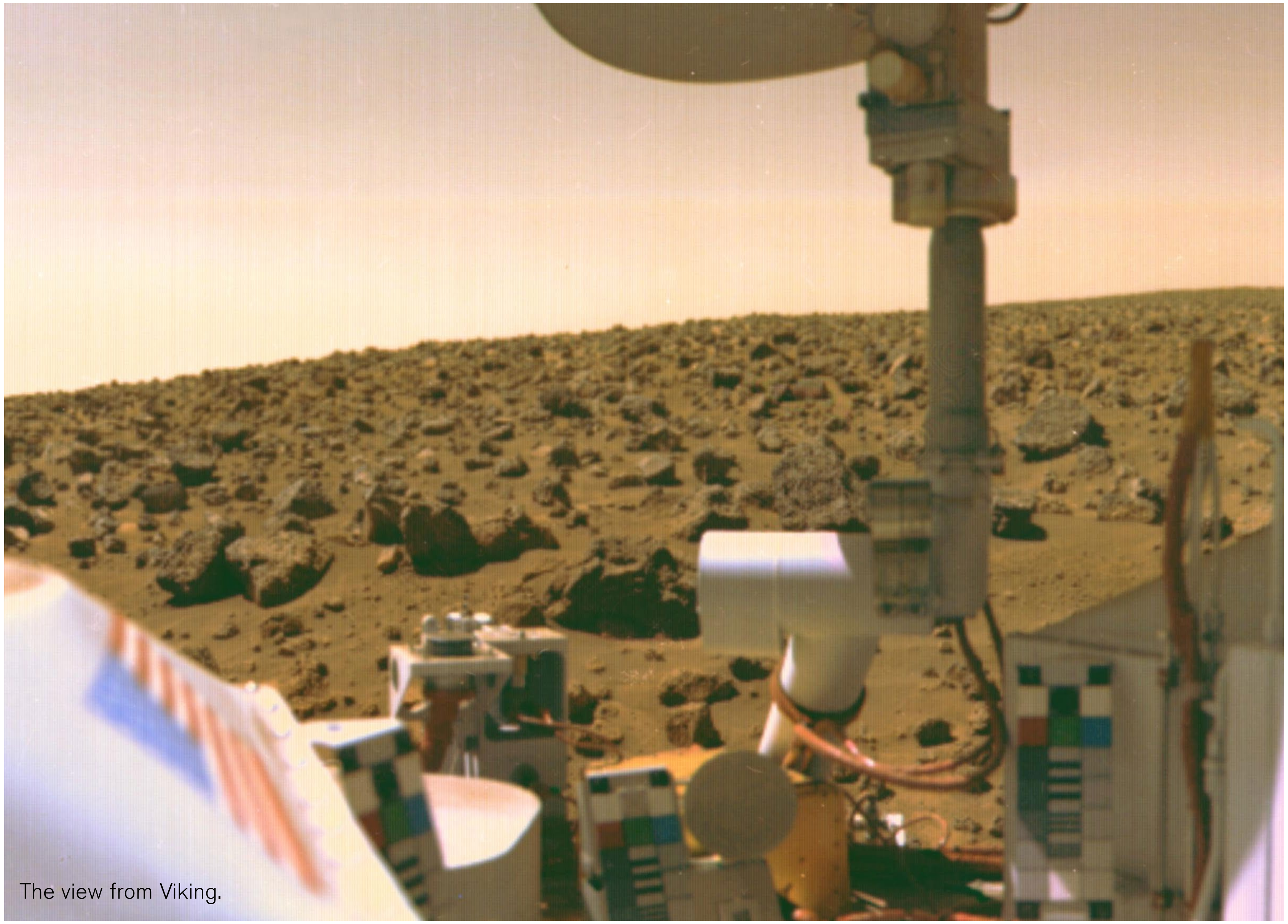
The opportunity to discover signs of extraterrestrial life provides a new scientific incentive for a sustainable base on the lunar surface. The moon is well known for its romantic appeal, but astrobiology offers a twist on this notion. Here’s hoping that the moon will inform our civilization that we are not alone and that someone else is waiting for us out there.

Gilbert V. Levin is an engineer and inventor.
He was the principal investigator of the Labeled
Release experiment on NASA Viking missions
to Mars in the 1970s.

SPACE

I'm Convinced We Found Evidence of Life on Mars in the 1970s

The Labeled Release experiment on the Viking mission reported positive results, although most have dismissed them as inorganic chemical reactions



The view from Viking.

NASA

We humans can now peer back into the virtual origin of our universe. We have learned much about the laws of nature that control its seemingly infinite celestial bodies, their evolution, motions and possible fate. Yet, equally remarkable, we have no generally accepted information as to whether other life exists beyond us or whether we are, as was Samuel Coleridge's Ancient Mariner, "alone, alone, all, all alone, alone on a wide wide sea!" We have made only one exploration to solve that primal mystery. I was fortunate to have participated in that historic adventure as experimenter of the Labeled Release (LR) life-detection experiment on NASA's spectacular Viking mission to Mars in 1976.

On July 30, 1976, the LR returned its initial results from Mars. Amazingly, they were positive. As the experiment progressed, a total of four positive results, supported by five varied controls, streamed down from the twin Viking spacecraft that landed some 4,000 miles apart. The data curves signaled the detection of microbial respiration on the Red Planet. The curves from

Mars were similar to those produced by LR tests of soils on Earth. It seemed we had answered that ultimate question.

When the Viking Molecular Analysis Experiment failed to detect organic matter, the essence of life, however, NASA concluded that the LR had found a substance mimicking life, but not life. Inexplicably, over the 43 years since Viking, none of NASA's subsequent Mars landers has carried a life-detection instrument to follow up on these exciting results. Instead the agency launched a series of missions to Mars to determine whether there was ever a habitat suitable for life and, if so, eventually to bring samples to Earth for biological examination.

NASA maintains the search for alien life among its highest priorities. On February 13, 2019, NASA administrator Jim Bridenstine said we might find microbial life on Mars. Our nation has now committed to sending astronauts to Mars. Any life there might threaten them, and us, on their return. Thus, the issue of life on Mars is now front and center.

Life on Mars seemed a long shot. On the other hand, it would take a near miracle for Mars to be sterile. NASA scientist Chris McKay once said that Mars and Earth have been "swapping spit" for billions of years, meaning that, when either planet is hit by comets or large meteorites, some ejecta shoot into space. A tiny fraction of this material eventually lands on the other planet, perhaps infecting it with microbiological hitchhikers. That some Earth microbial species could survive the Martian environment has been demonstrated in many laboratories. There are even reports of the survival of microorganisms exposed to naked space outside the International Space Station (ISS).

NASA's reservation against a direct search for microorganisms ignores the simplicity of the task accomplished by Louis Pasteur in 1864. He allowed microbes to contaminate a hay-infusion broth, after which bubbles of their expired gas appeared. Prior to containing living microorganisms, no bubbles appeared. (Pasteur had earlier determined that heating, or pasteurizing, such a substance would kill the microbes.) This elegantly simple test, updated to substitute modern microbial nutrients with the hay-infusion products in Pasteur's, is in daily use by health authorities around the world to examine potable water. Billions of people are thus protected against microbial pathogens.

This standard test, in essence, was the LR test on Mars, modified by the addition of several nutrients thought to broaden the prospects for success with alien organisms, and the tagging of the nutrients with radioactive carbon. These enhancements made the LR sensitive to the very low microbial populations postulated for Mars, should any be there, and reduced the time for detection of terrestrial microorganisms to about one hour. But on Mars, each LR experiment continued for seven days. A heat control, similar to Pasteur's, was added to determine whether any response obtained was biological or chemical.

The Viking LR sought to detect and monitor ongoing metabolism, a very simple and fail-proof indicator of living microorganisms. Several thousand runs were made, both before and after Viking, with terrestrial soils and microbial cultures, both in the lab and in extreme natural environments. No false positive or false negative result was ever obtained. This strongly supports the reliability of the LR Mars data, even though their interpretation is debated.

In her recent book *To Mars with Love*, my LR co-experimenter Patricia Ann Straat provides much of the scientific detail of the Viking LR at the lay level. Scientific papers published about the LR are available on my Web site.

In addition to the direct evidence for life on Mars obtained by the Viking LR, evidence supportive of, or consistent with, extant microbial life on Mars has been obtained by Viking, subsequent missions to Mars and discoveries on Earth:

- Surface water sufficient to sustain microorganisms was found on Mars by Viking, Pathfinder, Phoenix and Curiosity;
- Ultraviolet (UV) activation of the Martian surface material did not, as initially proposed, cause the LR reaction: a sample taken from under a UV-shielding rock was as LR-active as surface samples;
- Complex organics, have been reported on Mars by Curiosity's scientists, possibly including kerogen, which could be of biological origin;
- Phoenix and Curiosity found evidence

that the ancient Martian environment may have been habitable.

- The excess of carbon 13 over carbon 12 in the Martian atmosphere is indicative of biological activity, which prefers ingesting the latter;
- The Martian atmosphere is in disequilibrium: its CO_2 should long ago have been converted to CO by the sun's UV light; thus, the CO_2 is being regenerated, possibly by microorganisms as on Earth;
- Terrestrial microorganisms have survived in outer space outside the ISS;
- Ejecta containing viable microbes have likely been arriving on Mars from Earth;
- Methane has been measured in the Martian atmosphere; microbial methanogens could be the source;
- The rapid disappearance of methane from the Martian atmosphere requires a sink, possibly supplied by methanotrophs that could co-exist with methanogens on the Martian surface;
- Ghostlike moving lights, resembling will-o'-the-wisps on Earth that are formed by spontaneous ignition of methane, have been video-recorded on the Martian surface;
- Formaldehyde and ammonia, each possibly indicative of biology, are claimed to be in the Martian atmosphere;
- An independent complexity analysis of the positive LR signal identified it as biological;
- Six-channel spectral analyses by Viking's imaging system found terrestrial lichen and green patches on Mars rocks to have the identical color, saturation, hue and intensity;
- A wormlike feature was in an image taken by Curiosity;
- Large structures resembling terrestrial stromatolites (formed by microorganisms) were found by Curiosity; a statistical analysis of their complex features showed less than a 0.04 percent probability that the similarity was caused by chance alone;
- No factor inimical to life has been found on Mars.

In summary, we have: positive results from a widely used microbiological test; supportive responses from strong and varied controls; duplication of the LR results at each of the two Viking sites; replication of the experiment at the two sites; and the failure over 43 years of any experiment or theory to provide a definitive nonbiological explanation of the Viking LR results.

What is the evidence against the possibility of life on Mars? The astonishing fact is that there is none. Furthermore, lab studies have shown that some terrestrial microorganisms could survive and grow on Mars.

NASA has already announced that its 2020 Mars lander will not contain a life-detection test. In keeping with well-established scientific protocol, I believe an effort should be made to put life-detection experiments on the next Mars mission possible. My co-experimenter and I have formally and informally proposed that the LR experiment, amended with an ability to detect chiral metabolism, be sent to Mars to confirm the existence of life: nonbiological chemical reactions do not distinguish between "left-handed" and "right-handed" organic molecules, but all living things do.

Moreover, the Chiral LR (CLR) could confirm and extend the Viking LR findings. It could determine whether any life detected were similar to ours or whether there was a separate genesis. This would be a fundamental scientific discovery in its own right. A small, lightweight CLR has already been designed and its principle verified by tests. It could readily be turned into a flight instrument.

Meanwhile a panel of expert scientists should review all pertinent data of the Viking LR together with other and more recent evidence concerning life on Mars. Such an objective jury might conclude, as I did, that the Viking LR did find life. In any event, the study would likely produce important guidance for NASA's pursuit of its holy grail.

John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science, The End of War* and *Mind-Body Problems*, available for free at mindbodyproblems.com.

CROSS-CHECK

String Theory Does Not Win a Nobel, and I Win a Bet

Science writer John Horgan wins a 2002 bet with physicist Michio Kaku that by 2020 no unified theory of physics will win a Nobel Prize

SCULPTOR AND ENGRAVER: ERIK LINDBERG (1902), PHOTOGRAPHER: JONATHUNDER (2008-11-01) WIKIPEDIA

I just won a bet I made in 2002 with physicist Michio Kaku. I bet him $1,000 that "by 2020, no one will have won a Nobel Prize for work on superstring theory, membrane theory, or some other unified theory describing all the forces of nature." This year's Nobel Prize in Physics, which recognized solid work in cosmology (yay Jim Peebles!) and astronomy, was Kaku's last chance to win before 2020.

Kaku and I made the bet under the auspices of Long Bets, a "public arena for enjoyably competitive predictions, of interest to society, with philanthropic money at stake." Long Bets is a project of the Long Now Foundation, which Stewart Brand and others created in 1996 to promote "long-term thinking." Folks like Warren Buffet, Christof Koch, Freeman Dyson, Ray Kurzweil, Gordon Bell, Eric Schmidt, Steven

Pinker and Ted Danson have made hundreds of bets on predictions involving science, politics, the environment, economics, sports, you name it. Proceeds of bets go to a charity chosen by the winner. Kaku and I each put up $1,000 for our wager. Since I won, $2,000 goes to the Nature Conservancy. If Kaku had won, the money would have gone to National Peace Action.

Physicist Lee Smolin, a proponent of a rival to string theory called loop-space theory, was supposed to bet against me, but after fussing over the wording of the wager, he backed out. Smart move, Lee. [See Smolin's comment below.] Physicists have yet to produce any empirical evidence for either string theory, which was invented more than 40 years ago, loop-space theory or any other unified theory. They don't even have good ideas for obtaining evidence.

Below are the arguments that Kaku and I presented in 2002. In my argument I predicted that "over the next 20 years, fewer smart young physicists will be attracted to an endeavor that has vanishingly little hope of an empirical payoff." I'm not sure we've reached that point yet. But I hold by my prediction that someday we will look back at the search for a unified theory as a "religious" rather than scientific quest, which never had any hope of being fulfilled.

MICHIO KAKU'S 2002 ARGUMENT

It is often forgotten that physics is mainly done indirectly. Thus, we know that the sun is made of hydrogen gas, yet no one has ever visited the sun. We know that black holes exist in space, yet they are invisible by definition. We know that the big bang took place approximately 15 billion years ago, yet no one was there to witness it. We know these things, because we have indirect evidence or "echoes," such as sunlight and characteristic radiation from black holes and creation. Likewise, you do not need to build an atom smasher the size of the galaxy to prove string theory or M-theory (the leading and, in fact, only candidate for a theory of everything). Instead we need to look for echoes from the 10th and 11th dimensions as follows: (a) Within a few years, the Large Hadron Collider, the largest atom smasher on Earth, will be turned on outside Geneva, Switzerland. It might be able to find "sparticles" or super particles, that is, higher vibrations or octaves of the superstring. (b) Invisible dark matter, which makes up 90 percent of the matter in the universe, might be shown to consist of sparticles like the photino. This might also verify string theory. (c) In this decade, gravity-wave detectors should be able to record shock waves from colliding black holes, which might reveal the first quantum correction to Einstein's original theory of 1915. These quantum corrections can be compared with those predicted by string theory. (d) Within 20 years NASA plans to send three gravit-wave detectors into outer space. They should be sensitive enough to pick up the shock waves from the big bang itself created a fraction of a second after the instant of creation. This should be able to prove or disprove string theory. Personally, I feel no need to prove the theory experimentally, since I believe it can be proven using pure mathematics. A theory of everything is also a theory of everyday energies, where we find familiar electrons, protons and atoms. If we can solve the theory mathematically, then we should be able to calculate the properties of electrons, protons and atoms from pure mathematics. If the results disagree with known data, then string theory will be shown to be a "theory of nothing." If the numbers agree, however, then it will be heralded as the greatest achievement of the human mind. We will have "read the mind of God." So what prevents us from simply solving the theory and comparing the results with nature? The problem is that the theory is smarter than we are. No one on this planet is smart enough to solve this theory. The smartest people on Earth are working on this problem and have so far failed. (This is because the theory was discovered purely by accident in 1968. We were never supposed to see this theory in the 20th century. The mathematics necessary to solve the theory have not yet been discovered.) Because string theory has near-miraculous breakthroughs every eight to10 years, we can expect two more breakthroughs in the theory before 2020 and hence might be able to solve this theory by then. Perhaps someone reading this bet will be inspired to mathematically solve this theory completely. Maybe that person will then receive a telephone call from Sweden.

JOHN HORGAN'S 2002 ARGUMENT

In purely intellectual terms, a unified theory of physics would be the greatest of all scientific achievements. It would culminate the ancient human quest for knowledge, which began when the first of our ancestors asked, "Why?" It would yield the basic rules governing the entire universe, from the smallest to the largest scales. It would tell us how the universe came into being and why it took this particular form, which permitted our existence. It might even reveal our ultimate cosmic fate. At least, that's what seekers of a unified theory hope and what I used to believe. In the early 1990s I came to suspect that the quest for a unified theory is religious rather than scientific. Physicists want to show that all things came from one thing: a force, or essence, or membrane wriggling in 11 dimensions, or something that manifests perfect mathematical symmetry. In their search for this primordial symmetry, however, physicists have gone off the deep end, postulating particles and energies and dimensions whose existence can never be experimentally verified. The Superconducting Supercollider, the monstrous particle accelerator that Congress canceled in 1993, would have been 54 miles in circumference. Gaining access to the infinitesimal microscales where superstrings supposedly wriggle would require an accelerator 1,000 light-years around. (The entire solar system is only one light-day around.)

It is this problem that makes me confident I will win this bet. The Nobel Prize judges have always been sticklers for experimental proof. The dream of a unified theory, which some evangelists call a "theory of everything," will never be entirely abandoned. But I predict that over the next 20 years, fewer smart young physicists will be attracted to an endeavor that has vanishingly little hope of an empirical payoff. Most physicists will come to accept that nature might not share our passion for unity. Physicists have already produced theories—Newtonian mechanics, quantum mechanics, general relativity, nonlinear dynamics—that work extraordinarily well in certain domains, and there is no reason why there should be a single theory that accounts for all the forces of nature. The quest for a unified theory will come to be seen not as a branch of science, which tells us about the real world, but as a kind of mathematical theology. By the way, I would be delighted to lose this bet.

Postscript: This is the second Nobel-related bet I've won. In 1994 I bet physicist Michael Riordan a case of California wine that his Stanford colleague Andrei Linde would not win a Nobel Prize by the end of the century for his work on inflation, a theory of cosmic creation. Two decades later inflation still hasn't won a prize.

Update: String critic Peter Woit comments on my victory over Kaku at his blog "Not Even Wrong."

Comment from Lee Smolin: Dear John, In your recent SA blog about winning your bet with Kaku (congratulations!), I read about myself: "Physicist Lee Smolin, a proponent of a rival to string theory called loop-space theory, was supposed to bet against me, but after fussing over the wording of the wager, he backed out. Smart move, Lee. Physicists have yet to produce any empirical evidence for either string theory, which was invented more than 40 years ago, loop-space theory or any other unified theory. They don't even have good ideas for obtaining evidence."

It took me an e-mail search to recall this, and I was amused to find that my "fussing" was over two issues. First, the use of the Nobel Prize as an indicator. Second, I was trying—apparently unsuccessfully—to explain to you that we did then have good ideas for obtaining evidence about the geometry of spacetime empirically. These had to do with using gamma-ray bursts and other high-energy astrophysics to discover or, failing that, constrain the breaking of Lorentz symmetry at the Planck scale. That was—and is—considered a possible route to obtaining evidence about QG [quantum gravity] as there were then certain QG models that predicted such breaking, and it was likely that near-future experiments (that is, Fermi) could falsify those models. And indeed, that is exactly what happened over the past 15 years, as experimental limits on such breaking were raised into the Planck regime.

In light of these results, many of us in QG focus on models and theories that are either Lorentz invariant at the Planck scale (such as certain spin foam models) or suppress the effects of symmetry breaking to at least second order in energies in Planck units (like certain deformed-symmetry models). Thus, the important point is that experiment has already played a significant role in ruling out certain models of quantum spacetime. And this story is not over, as we await new data—especially from very high energy neutrinos.

Thanks, Lee.

Celestial Movement

The sky is always changing. The planets move overhead as they trace their paths around the sun, and the moon rotates through the heavens as it circles our own world. Although the stars that provide their backdrop stay fixed in relation to one another, they, too, spin above as Earth makes its daily revolution and its yearly passage around the sun. To appreciate this ever changing view, grab these sky maps, go outside at night and look up!

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Astronomical Events
December 2019—January 2020

December	Event
4	Moon: first quarter
5	Moon at apogee (404,446 km), apparent diameter 29´ 50´´
10	Dusk: Venus 2° south of Saturn 1 hour after sunset
	Moon near Aldebaran in constellation Taurus
12	Moon: full moon
13	Moon reaches northernmost declination
14	Maximum of Geminids meteor shower
18	Moon at perigee (370,265 km), apparent diameter 32´ 05´´
19	Moon: last quarter
22	Winter solstice
	Morning sky: waning crescent moon right of Mars in constellation Libra
23	Maximum of Ursids meteor shower
	Morning sky: waning crescent moon left of Mars in constellation Libra
26	Moon: new moon (annular eclipse of the sun, visible from Saudi Arabia, India, Sumatra, Borneo)
	Moon reaches southernmost declination
27	Jupiter in conjunction with sun
	Dusk: waxing crescent moon left of Saturn
28	Dusk: waxing crescent moon below Venus

December 2019—January 2020: Visibility of the planets

December starts with three planets in the evening sky. But as the visibility of Venus steadily improves, Jupiter and Saturn are about to leave the celestial stage. Both giant planets are going to be in conjunction with the sun (on December 27 and January 12, respectively).

Mercury can be seen in the morning sky in early December. About 50 minutes before sunrise we can spot the innermost planet of our solar system low in the east-southeast. By the time Mercury has reached a height of about 10°, its light will fade away in the brightening sky. As Mercury is moving eastward toward the sun, the chances of spotting the planet decrease day by day. By mid-December the planet will no longer be visible. Mercury is in superior conjunction with the sun on January 10 and will reappear in the evening sky at the end of January.

Venus is the "evening star" above the southwestern horizon and much brighter than Jupiter and Saturn. Venus is moving faster in an eastward direction than the sun does. Therefore, its elongation increases from 28° at the beginning of December to 40° at the end of January. While moving along the ecliptic, Venus leaves Jupiter behind and will pass Saturn on December 10 in the constellation Sagittarius. After Christmas, Venus is the only bright planet visible in the evening sky. By the end of January Venus sets about three hours after sunset.

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Astronomical Events
December 2019—January 2020

January • Event

2	**Moon at apogee (404,580 km), apparent diameter 29´ 50˝**
3	**Moon: first quarter**
4	**Maximum of Quadrantids meteor shower**
5	**Earth at perihelion (147,1 million km)**
7	**Evening sky: moon near Aldebaran in constellation Taurus**
10	**Moon reaches northernmost declination**
	Mercury in superior conjunction
	Moon: full moon (Penumbral Lunar Eclipse, not visible from the Americas except Canada)
12	**Moon near Regulus in constellation Leo**
13	**Saturn in conjunction with sun**
	Moon at perigee (365,958 km), apparent diameter 32´ 40˝
17	**Moon: last quarter**
20	**Dawn: waning crescent moon upper right of Mars in constellation Ophiuchus**
22	**Dawn: waning crescent moon upper right of Jupiter in constellation Sagittarius**
23	**Moon reaches southernmost declination**
24	**Moon: new moon**
27	**Dusk: moon below Venus in constellation Aquarius**
29	**Moon at apogee (405,393 km), apparent diameter 29´ 47˝**

December 2019—January 2020: Visibility of the planets

December starts with three planets in the evening sky. But as the visibility of Venus steadily improves, Jupiter and Saturn are about to leave the celestial stage. Both giant planets are going to be in conjunction with the sun (on December 27 and January 12, respectively).

Mars is a morning-sky object and moves slowly eastwards through the constellation Libra during December. The red planet is not very bright, but can easily be distinguished from the stars by its characteristic color. One to two hours before sunrise Mars is worth a look. In mid-January, Mars passes Antares, the brightest star in constellation Scorpius. Because Antares also shines red, it is always a delight to observe these reddish spots so close together. Due to the similarity in their reddish hues, the ancient Greeks used similar names for them: Ares for the planet and Antares (meaning "opponent of Ares") for the stars. Both celestial objects were associated with blood and war.

Jupiter might be seen very low in the western sky shortly after sunset in the beginning of December. But its visibility period is now quickly coming to an end. On December 27 Jupiter is in conjunction with the sun—that is, the moment when the planet is passed by our star along its path along the ecliptic on the sky. In mid-January, Jupiter reappears in the morning sky about one hour before sunrise.

Saturn is in the evening sky at the beginning of December. Before its visibility period ends at about Christmas, Saturn is in close conjunction with Venus on December 10. Conjunction with the sun is on January 13 and we have to wait until February for the planet to reappear in the morning sky.

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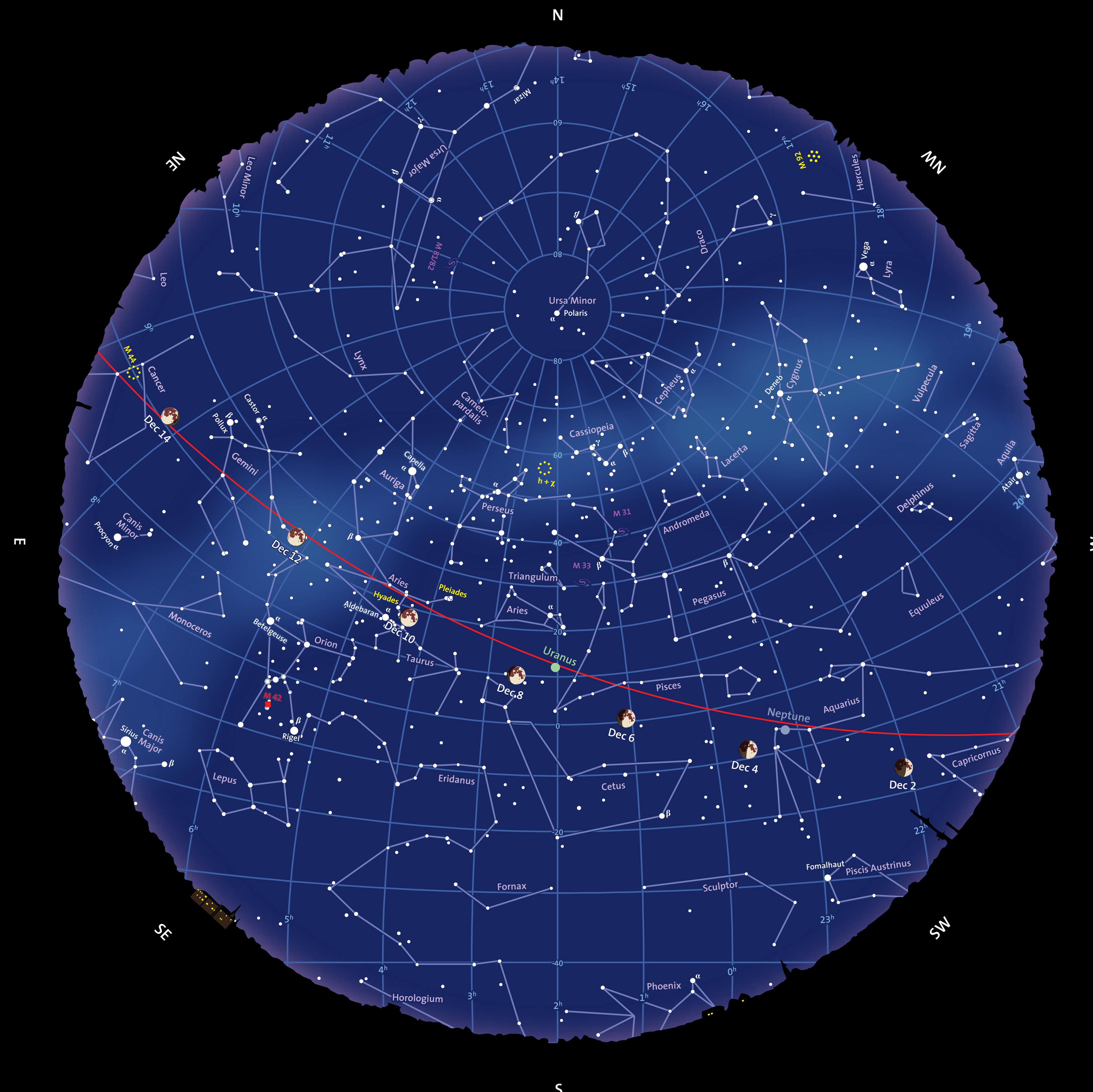
SKY REPORT

December

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the “N” on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.



The reference point is 100° W and 40° N and the exact time is 10 p.m. EST or 9 p.m. CST.

−1	0	1	2	3	4	5

Apparent magnitudes

- Open Cluster
- Globular Cluster
- Galaxy
- Nebula

ERNST VON VOIGT

January

Hold this sky map so that the direction you are facing is located at the bottom of the page. For example, if you are looking north, rotate the map 180 degrees so that the "N" on the edge of the circle is down. White dots denote stars, purple lines mark constellations, and yellow symbols mark bright objects such as star clusters. The red line running from one side of the sky to the other represents the ecliptic—the plane of our solar system and the path the planets take around the sun. The moon also orbits closely in line with the ecliptic, so it can be found here.

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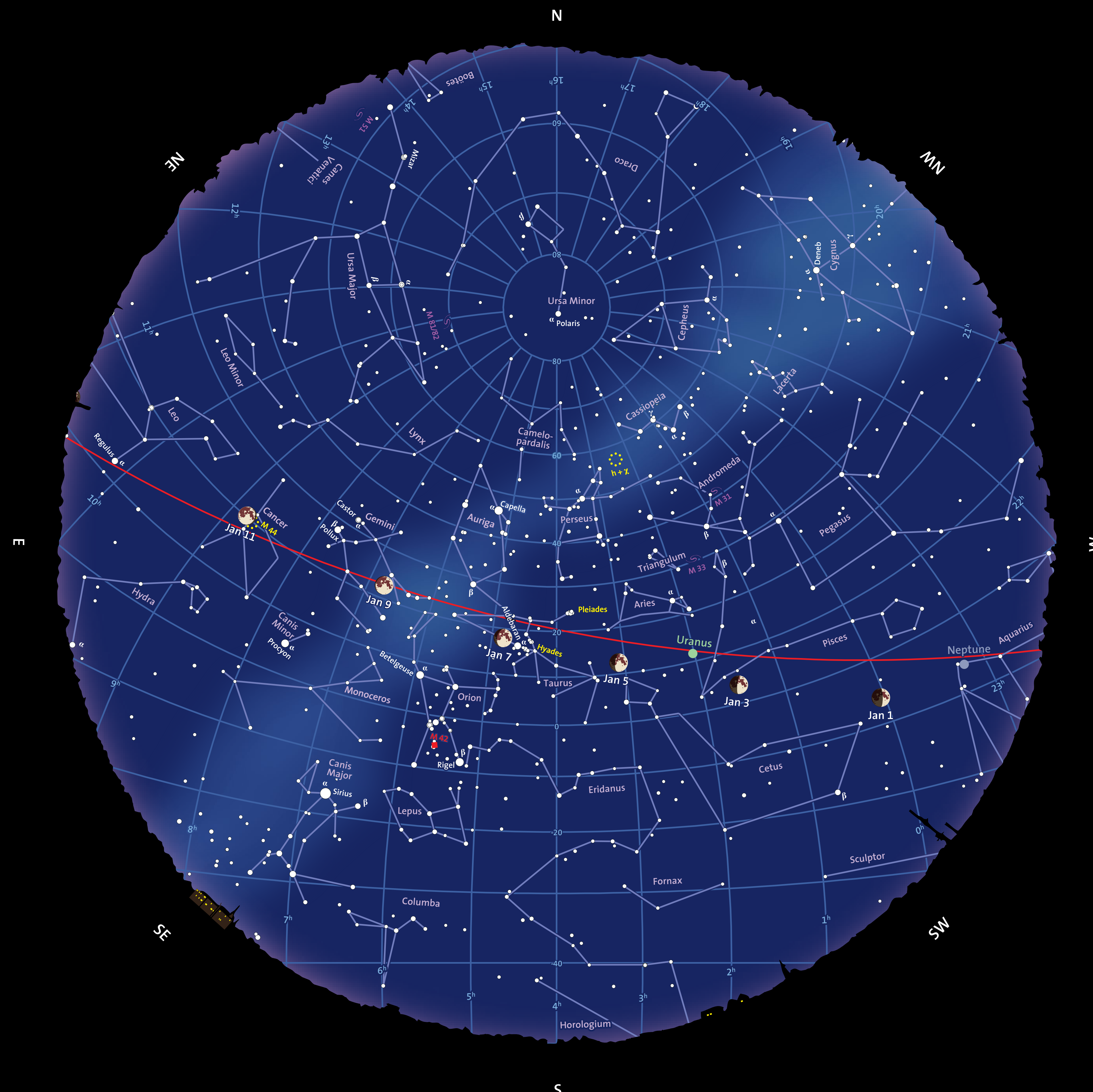

●	●	●	•	•	•	·
–1	0	1	2	3	4	5

Apparent magnitudes

- Open Cluster
- Globular Cluster
- Galaxy
- Nebula

ERNST VON VOIGT

SCIENTIFIC AMERICAN Space & Physics

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