Discovery

Research at Princeton 2020
Magazine

PRINCETON
UNIVERSITY

Crowdsourcing solutions from a global population of scientists and scholars

Pablo Debenedetti
Dean for Research
Class of 1950 Professor in Engineering and Applied Science
Professor of Chemical and Biological Engineering

PHOTO BY DAVID KELLY CROW

As Dean for Research, it is my job to steward and advocate for the research activities of Princeton faculty, students and staff. Through these pages, I invite you to experience the fascinating and impactful research happening across the disciplines at Princeton, from science and engineering to the social sciences, humanities and the arts.

Our nation's tradition of welcoming international scholars makes our universities some of the best places to study, conduct research and contribute discoveries that fuel jobs and economic growth.

Nearly a third of all U.S.-based Nobel laureates were born outside the United States. Innovators such as Alexander Graham Bell and Nikola Tesla, and deep thinkers such as Albert Einstein sought the U.S. for its opportunities, freedoms and welcoming attitude. International scholars make up 30% of Princeton's faculty and 45% of Princeton's graduate student body.

These scientists and scholars help make America prosperous, but the benefits of their contributions accrue far beyond our borders. U.S.-trained scientists leave our shores and go on to invent new technologies, start companies, teach at universities, run for public office, lead nonprofits and otherwise contribute to society and our quest for knowledge.

Recent changes to immigration policies have led to visa delays and other obstacles for international students and scholars planning to study or work in the United States. These policies threaten to constrict our longstanding crowdsourcing of talent and initiative. Already the number of international science and engineering graduate students enrolling at U.S. institutions shows signs of slowing, according to a 2019 report from the Council of Graduate Schools.

While Princeton takes concerns about inappropriate foreign influence in research seriously, we believe that openness, the free exchange of ideas, and the ability to continue to attract top talent from around the world are essential not just to the University's research enterprise, but for our country's continued ability to be the world's leader in innovation and knowledge creation.

Instead of putting obstacles in talent's way, let's welcome inquisitive minds who will put their training to work, finding solutions to present and future problems, here and around the world.

Discovery

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Research at Princeton

2020

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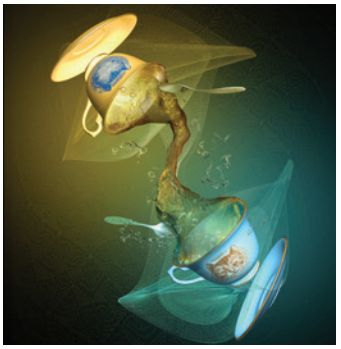

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Cover: Quantum computing promises new capabilities and new power. Page 12. Illustration by J.F. Podevin

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Briefs

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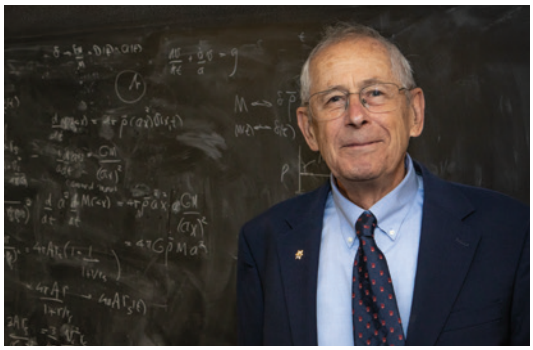


AWARDS

Nobel Prize awarded for discoveries in cosmology

Princeton University professor emeritus James Peebles was awarded the 2019 Nobel Prize in Physics for contributions to our understanding of the evolution of the universe. Peebles, the Albert Einstein Professor of Science, Emeritus, is perhaps best known for the theory of cold dark matter, which he initially proposed in 1982, and his pioneering efforts in identifying cosmic background radiation as the remnant of the Big Bang. "His theoretical framework, developed over two decades, is the foundation of our modern understanding of the universe's history, from the Big Bang to the present day," the Royal Swedish Academy of Sciences stated in announcing the prize. **–Tom Garlinghouse**

DATA SCIENCE

Deep learning detects mutations behind autism

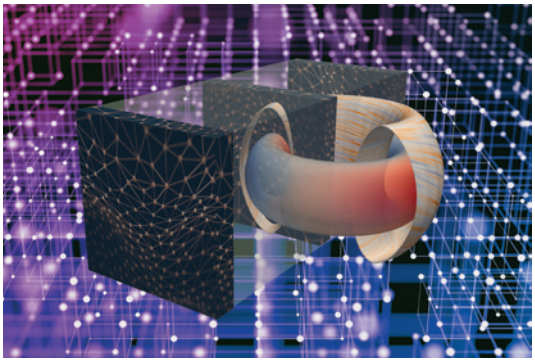
Using artificial intelligence, a Princeton-led team has decoded the impact of a new class of mutations in people with autism. These mutations are not in actual genes but instead lie in the 99% of the genome that regulates the genes. Published May 27, 2019, in the journal *Nature Genetics*, the study sorted among 120,000 mutations in 1,790 families with more than one child in which one child has autism spectrum disorder but the others do not. The team applied an AI technique called deep learning to discover patterns that are otherwise impossible to find. "This method provides a framework for doing this analysis with any disease," said Olga Troyanskaya, professor of computer science and the Lewis-Sigler Institute for Integrative Genomics. **–Steven Schultz**

BRAIN AND BEHAVIOR

Motion-capture technology assists in neuroscience studies

Bringing Hollywood motion-capture techniques to the laboratory, a new technology can automatically track animals' body parts in video to measure the behavior of animals with genetic mutations or following drug treatments, according to principal investigators Mala Murthy, professor of neuroscience, and Joshua Shaevitz, professor of physics and the Lewis-Sigler Institute for Integrative Genomics. "This is a flexible tool that can in principle be used on any video data," said Talmo Pereira, a graduate student in the Princeton Neuroscience Institute and the first author on the study, which appeared in the January 2019 issue of the journal *Nature Methods*. **–Liz Fuller-Wright**

IMAGE BY ELIOT FEIBUSH/PPPL AND JULIAN KATES-HARBECK/HARVARD UNIVERSITY



ENERGY

AI accelerates fusion energy research

Artificial intelligence could speed the development of safe, clean and abundant energy from fusion, the same process that powers the sun and stars. Scientists at the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) are using AI to forecast disruptions that can halt fusion reactions and damage the doughnut-shaped devices that house the reactions. Led by William Tang, a PPPL physicist and lecturer with the rank of professor at Princeton, the project has demonstrated the ability to predict disruptions within 30 milliseconds, the amount of time required for use in ITER, the next-generation fusion facility under construction in France. "This opens a promising new chapter in the effort to bring unlimited energy to Earth," said Steven Cowley, PPPL director and Princeton professor of astrophysical sciences. **–John Greenwald**

PUBLIC POLICY

People adapt to societal diversity

Initially threatened by change, people adapt to societal diversity over time, according to researchers at Princeton University and the University of Oxford. Their findings were published May 6, 2019, in the *Proceedings of the National Academy of Sciences*. The team examined 22 years of psychological, sociological and demographic data from more than 338,000 respondents in 100+ countries. Although over two-year periods diversity acted to reduce social trust, over a 12-year period, diversity led to greater intergroup contact that increased social trust and offset the negative short-term influence. "If you give people who are different from you half a chance, they will integrate into society pretty well," said Douglas Massey, the Henry G. Bryant Professor of Sociology and Public Affairs at Princeton's Woodrow Wilson School.
–B. Rose Kelly

INNOVATION

Princeton appoints first vice dean for innovation

Rodney Priestley, professor of chemical and biological engineering and a leading researcher in the area of complex materials and processing, has been named Princeton University's inaugural vice dean for innovation, effective Feb. 3, 2020. The newly created position provides academic leadership for innovation and entrepreneurship activities across campus. Priestley will oversee efforts to grow Princeton's culture of innovation by expanding collaborations with industry, entrepreneurs, alumni and other potential partners. He has published nearly 100 articles, is co-inventor on four patent-pending technologies in drug-delivery and polymer colloids, and is co-founder of two companies working to translate research into technologies or products.
–Catherine Zandonella

PHOTO BY DAVID KELLY CROW

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HUMANITIES

Finding the Lost Generation

A new interactive website provides scholars and the public with insights into the Lost Generation, a group of writers and artists that came of age during World War I. The website is based on records, housed at the Princeton University Library, from Shakespeare and Company, an English-language book shop and lending library in Paris. During the 1920s and '30s, writers such as Ernest Hemingway, Gertrude Stein and others borrowed and purchased books from the shop. Created by Joshua Kotin, associate professor of English, in collaboration with graduate and undergraduate students and Princeton's Center for Digital Humanities, the Shakespeare and Company Project makes available borrowing histories, financial transactions, maps and other documents.
Visit **shakespeareandco.princeton.edu.**
–Catherine Zandonella

Deborah Vischak reveals

the dynamics of ancient Egypt

By Tom Garlinghouse

Ancient Egypt, with its monumental pyramids, temples and sculptures, is often seen as a civilization frozen in time, as unchanging and predictable, perhaps, as the annual rise and fall of the Nile River, an event so regular that the Egyptians based their calendar on it.

"As popular as ancient Egypt is for many people, there is nonetheless a sense, even today, that it almost wasn't real," said Deborah Vischak, assistant professor of art and archaeology, and a specialist in Egyptology.

Vischak wants to change this perception.

For her, this conventional narrative doesn't capture the massive sweep of time — encompassing a span of over 3,000 years — represented by Egyptian culture and society. Nor does it give much insight into the everyday lives of people, both commoners and elites, from that era. Ancient Egypt, Vischak said, was much more dynamic and creative than the more traditional narrative suggests.

"Ancient Egyptians were people like any other," she said. "They cared about their jobs, their families — they fought with each other, they fell in love."

To capture this more nuanced picture of ancient Egypt and its inhabitants, Vischak and a team of American and Egyptian archaeologists are excavating at one of the oldest sites in Egypt, Abydos. With a history extending back 5,000 years, Abydos is located in the southern part of the country, nearly 400 kilometers south of Cairo along the Nile. "It's the burial place of the very first kings of Egypt," Vischak said.

Today, few standing monuments survive at Abydos, and rural villages encroach and encircle the desert site, located on the west bank of the Nile between the edge of the river valley and the enclosing desert cliffs to the west. Spanning nearly seven square kilometers, Abydos contains a rich collection of ancient material, including vast cemeteries and royal temples.

Chief among these are the Temple of Seti I, which is the main draw for most tourists, and the Shunet el-Zebib, a weathered mud-brick funerary monument belonging to one of Egypt's earliest kings, Khasekhemwy. The conservation of this 5,000-year-old monument — one of the oldest standing burial structures in the world — is an important part of the project.

Excavations at Abydos began in the late 1960s under veteran Egyptologist David O'Connor of New York University. For over 50 years, O'Connor explored the vast site, slowly piecing together its complex history, and often focusing on the less explored aspects of Egyptian history. Vischak, who became co-director of the project in 2018 along with Matthew Adams of New York University, has carried on O'Connor's vision.

Vischak, Adams and Reis Ibrahim Mohamed 'Ali, the archaeological foreman, are concentrating their research efforts at a non-royal cemetery at the north end of the site, near the Shunet. The cemetery dates primarily to the Old Kingdom (ca. 2700–2000 BCE), though it was used in later periods. "What I want to look at is how this cemetery speaks to us today," Vischak said. "What can we tell about the community by what they left behind for us?"

Last year, Vischak uncovered a diverse array of Old Kingdom artifacts in the cemetery, including pottery sherds, beads, jewelry, ceramic vessels, and numerous funerary and votive offerings.

Collectively the cemetery and these artifacts document a time when Abydos had lost its prominence as a royal site. Djoser, an Old Kingdom pharaoh and Khasekhemwy's heir, left the royal ancestral burial grounds of Abydos behind, moving his funerary monument north close to the capital city of Memphis, near modern-day Cairo. Abydos was transformed into something of a backwater.

Vischak is interested in what this transition meant to the area's inhabitants. What economic, social and political changes occurred as a result of this alteration in their fortunes?

Vischak's findings indicate that although the kings left Abydos behind, the local community continued on, and they took part in the same religious and funerary traditions shared across the country, though in a significantly different kind of sacred landscape. In the next millennium, 700 years later, the site became an important sacred center, attracting the devotees of Osiris, the Egyptian god of the underworld and the deity responsible for judging souls in the afterlife.

Through these excavations, the team is discovering that Egyptian history was not simply a long arc of people who had a uniform experience, but was much more nuanced. "It's all real history," Vischak said. "It was rich and complicated." ›

PHOTOS BY AYMAN DAMARANY

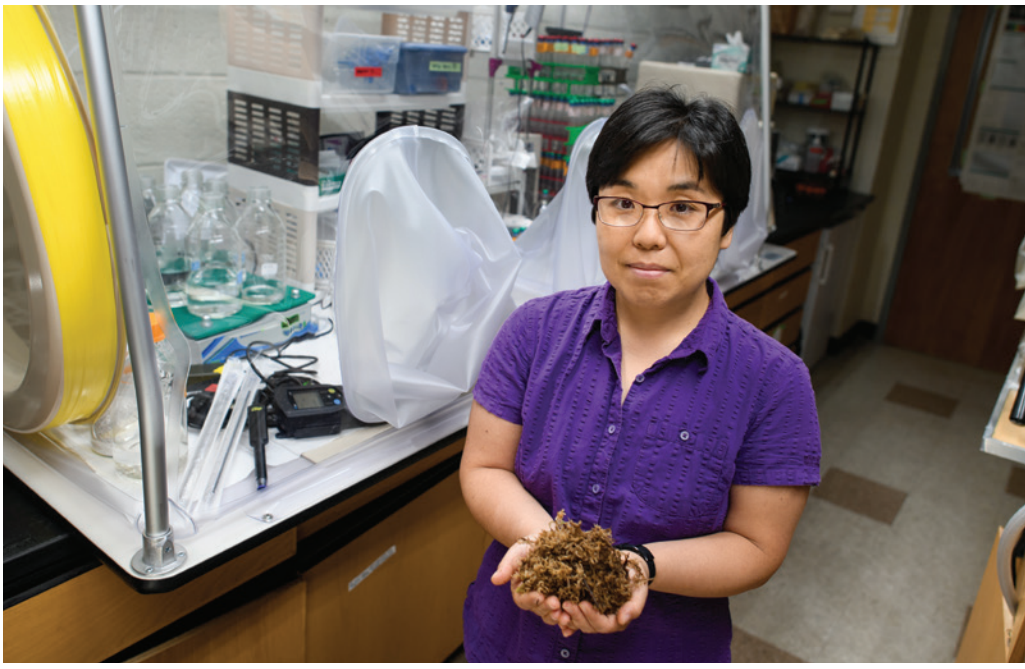
This early Old Kingdom cemetery at Abydos, home of Egypt's first pharaohs, tells of a time when the ancient site lost prominence as the kings moved their burials north, to the capital Memphis, near Cairo.

Deborah Vischak (left) with the head of the Egyptian crew, Reis Ibrahim Mohamed 'Ali, and Matthew Adams, co-director of the North Abydos Expedition.

"Ancient Egyptians were people like any other. They cared about their jobs, their families — they fought with each other, they fell in love."

Deborah Vischak
Assistant Professor of Art and Archaeology

PHOTO BY SAMEER A. KHAN/FOTOBUDDY



How wetlands contribute to climate change

Xinning Zhang studies the role that wetlands play in generating methane, a significant greenhouse gas.

Hemmed in on one side by towering redwoods and on the other by the Pacific Ocean, the vibrant coastal city of Santa Cruz, some 70 miles south of San Francisco, is a great place for a young person to experience nature. That's where Xinning Zhang, assistant professor of geosciences and the Princeton Environmental Institute, spent her childhood.

"Growing up there, you just can't help thinking about and caring about the environment," she said.

One of the environmental questions Zhang is exploring is why methane, a significant greenhouse gas, is increasing in the atmosphere. Although public focus has largely been on rising levels of carbon dioxide, methane is roughly 30 times more potent at trapping heat.

Most of us are aware that cows release methane, but wetlands are also a major source of the gas, formed when organic matter decomposes. The culprits are among the smallest living constituents of the soil — the microbes.

"The habitability of our planet really depends on microbes," Zhang said. "Microbes control oxygen in the atmosphere; they were the first life forms on Earth. They are hugely important."

Bogs host a community of microbes, including Archaea, which generate methane as a byproduct when they consume and digest components of organic matter. These "methanogens" thrive in oxygen-free environments like wet and boggy soils that typically occur in the wetlands' deeper levels.

However, researchers have been surprised to find that quite a lot of methane comes from the oxygen-rich peat and soil near the surface. The conundrum of how these methane-producing microbes, for which oxygen is toxic, can thrive in oxygen-rich settings has been termed the wetland paradox.

To explore this phenomenon, Zhang and Jared Wilmoth, a postdoctoral research associate on Zhang's team, analyzed peat samples collected from a bog in the Northeast U.S.

One set of samples was subjected to oxygen treatment followed by incubation under oxygen-free conditions. The other samples remained in an oxygen-free environment for the entire study period. Contrary to expectations, Zhang and her team found that the oxygen-treated peats produced a higher amount of methane than the peats maintained under continuously oxygen-free conditions.

To find out why, the researchers sequenced the genomes of all microbes found in the peat samples. They found that oxygen stimulated another group of microbes to break down constituents of peat that tend to be toxic, such as tannins. As these microbes break down the compounds, they also lower the toxicity threatening the entire microbial community, including methane-producing Archaea. The result is the creation of far more methane than expected.

Zhang's work, which is funded by the Princeton Environmental Institute's Carbon Mitigation Initiative, suggests that oxygen variability is an important control on wetland methane emissions. Her team is also exploring how hydrology, timescales of oxygen variability, and different soil chemistries influence microbial methane production. **–By Tom Garlinghouse**

A small number of wells produce large emissions

Wells that extract natural gas from underground often leak large amounts of methane, a powerful greenhouse gas, into the air. A team of Princeton researchers has found that, in one of the biggest gas-producing regions, most of these emissions come from a tiny subset of the wells, a finding with major implications for how to control the problem.

Researchers led by Mark Zondlo, an associate professor of civil and environmental engineering, spent two years sampling emissions from the Marcellus Shale, a basin that stretches from West Virginia to Pennsylvania to New York State. In research published in the journal *Environmental Science and Technology* in March 2019, the authors reported that 10% of wells account for more than three-quarters of gas leaked into the atmosphere as a byproduct of extraction. That has the equivalent greenhouse gas effect of adding 500,000 cars, or about 2% of the U.S. auto market, to the road.

This finding, however, may have a silver lining for mitigating impacts on the environment, Zondlo said, because fixing a relatively small number of these "superemitting" wells could lead to a major reduction in emissions. He cautioned that identifying the leakiest wells is not always easy, in part because well emissions can change over time.

The researchers said the emissions can result from a variety of practices, including the intentional opening of valves to relieve pressure at wells, or from valves that are unintentionally stuck open. Previous studies have looked at small samples of wells in Texas and West Virginia and reached similar conclusions about the impact of "superemitters." The new research is the first to look at operations over the most productive shale basin in the U.S. and represents the largest total number of wells measured.

David Lyon, a scientist at Environmental Defense Fund who has worked on previous methane emissions assessments, said: "The results from this study reinforce the urgent need to reduce methane leaks from Pennsylvania's existing unconventional gas wells. These leaks represent $70 million in wasted natural gas resources and have a short-term climate impact equivalent to that of nine coal-fired power plants."

Along with Zondlo, principal researchers on the team included Elie Bou-Zeid, professor of civil and environmental engineering, and Jeffrey Fitts, a former research scholar. All three were affiliated with Princeton's Andlinger Center for Energy and the Environment. Dana Caulton, a former postdoctoral researcher in Zondlo's lab, led the field sampling. Support for the research was provided in part by the National Oceanic and Atmospheric Administration.

–By Molly Seltzer

PHOTO COURTESY OF THE ZONDLO LAB

A small number of natural gas wells are "superemitters" of methane, according to a new study by researchers who measured the concentration of gases near wells in the Marcellus Shale basin.

Exploring free speech and corporate power: Sydney Jordan

PHOTO BY DENISE APPLEWHITE

Sydney Jordan

PHOTO BY DENISE APPLEWHITE

Annabel Barry

Sydney Jordan found inspiration for her thesis from a course on free speech in the internet age. "After coming to the conclusion that the government had limited ability to impose restrictions on companies' interaction with speech," Jordan said, "I wanted to explore whether corporations' own moral obligations might compel them to enact, or remove, particular restrictions."

Jordan "asks the questions that need to be asked," said her senior thesis adviser, Daniel Garber, the A. Watson Armour, III, University Professor of Philosophy.

A busy student athlete — Jordan was a three-year-starter on the women's basketball team — she credits Garber with helping her to unravel complicated ideas and conduct her research through a title-winning season her senior year.

Her thesis explores some modern examples of corporations' responses to free speech, including the NFL's response to Colin Kaepernick's protest and Twitter's hateful-conduct policy.

Jordan was the co-winner (with Annabel Barry) of Princeton's Moses Taylor Pyne Honor Prize, the highest general distinction given to an undergraduate. **–By Jenifer Jonson**

'Fever' and its meanings in English literature: Annabel Barry

The acknowledgments at the beginning of Annabel Barry's senior thesis start with a thank-you to her family, including her seven siblings, and end with a shout-out to Princeton's theatrical scene shop staff "for agreeing to operate some very heavy puppets."

At Princeton, Barry's talents ranged from theater and community service to peer academic advising. She earned the Pyne Prize alongside Sydney Jordan. Her academic accomplishments as a researcher and writer were forged in the English department, where she was one of three rising seniors to spend summer 2018 at Oxford through the Princeton Bread Loaf fellowship.

"At Oxford, I began to read Mary Wollstonecraft's feminist philosophy and travel writings," Barry said. Her thesis "describes the contradictions in Wollstonecraft's philosophy, which dreamed of an escape from the sexed body and the 'woman's fever' that cut her career short."

Professor of English Susan Wolfson described Barry's research as "an impressively ambitious, savvy adventure." **–By Jenifer Jonson**

Fracking and public health: Benjamin Jacobson

PHOTO BY STUART JACOBSON

Benjamin Jacobson

For his senior thesis, Benjamin Jacobson studied whether chemicals from fracking, the natural gas extraction process, interact with human DNA to affect the health of children.

Jacobson analyzed saliva samples from participants in the Fragile Families and Child Wellbeing Study, which since 1998 has followed children at risk due to poverty. Samples were collected in 2009 and again in 2015, a period during which the gas-extraction technology became more widely used in the United States.

Jacobson discovered that, during this six-year interval, children living near fracking sites experienced greater weight gain than children not exposed to fracking. He looked for markers on the children's DNA called methyl groups. "DNA methylation can act as a sort of switch to turn genes on and off," Jacobson said.

He found changes in DNA methylation on certain gene sequences involved in cholesterol transport and fat production levels, demonstrating a possible correlation that could be explored through further studies.
–By Tom Garlinghouse

Breaking new ground:
Lauren Auyeung

Lauren Auyeung's proposal to choreograph a hip-hop dance piece as her senior thesis work was a first in the 50-year history of Princeton's Lewis Center for the Arts' Program in Dance. No thesis project had previously explored this dance form.

Auyeung's work is set in the world of a hip-hop dance battle, following five individuals as they experience forces of competition, confrontation and insecurity from their surroundings.

Inspired by the physical virtuosity of hip-hop and urban dance, Auyeung seeks to investigate the movement vocabularies of hip-hop in abstracted form, reinterpreting them through her own creative voice. Her training included a course in her first year — the first hip-hop dance course offered at Princeton — called "Special Topics in Urban Dance: Hip-Hop Dance Practice and Culture," co-taught by breakdancing artist Raphael Xavier and performance scholar Joseph Schloss.

The piece was performed in the Lewis Center for the Arts' Hearst Dance Theater in April 2019. **—By Steve Runk**

PHOTO BY LARRY LEVANTI

Popping the ideological bubbles
of social media users

PHOTO BY EGAN JIMENEZ

Andy Guess's work shows that most people obtain their political news from numerous sources, not just partisan outlets.

When Facebook and Twitter gained popularity in the late 2000s, many believed their growth would have an impact in the political world — enhancing communication among communities, their representatives and the government.

Andy Guess became fascinated with the intersection of American politics and social media. For the past four years, his research has focused on how the internet and digital media shape attitudes and political behaviors.

"I work to reconstruct people's online information environments as best as possible. This involves trying to get a sense of what people actually see on social media platforms and what people do when they are browsing the internet," said Guess, an assistant professor of politics and public affairs at Princeton's Woodrow Wilson School of Public and International Affairs. He combines individual survey responses with online behavioral data to observe web-browsing behaviors, from how much time people spend on certain websites to who clicks on what stories.

One of the issues he has explored is how people receive and share information from preferred environments, whether Facebook, Twitter and other social media platforms or websites like *The New York Times*. Using surveys and behavioral data, Guess's recent work shows that people actually obtain their political news from numerous sources, not just partisan outlets.

"There's a common narrative that people on the right only read right-wing news and people on the left only read left-wing news," said Alexander Coppock, assistant professor of political science at Yale University. "Using his research design, Andy showed that's really not true. Most people are in the middle, and most people are getting a balanced news diet."

Guess's research also investigates "fake news" and how online misinformation can affect people's beliefs, decisions and voting patterns. He hopes that his work will give people the tools they need to inform themselves about questionable content online.

"Before Andy came along, we were analyzing survey responses and self-reported information about social media, or we were just analyzing social media on its own," Coppock said. "He was able to put those two together in a really important way and bring a new technological innovation to the table. His innovative research designs really set him apart in this area."

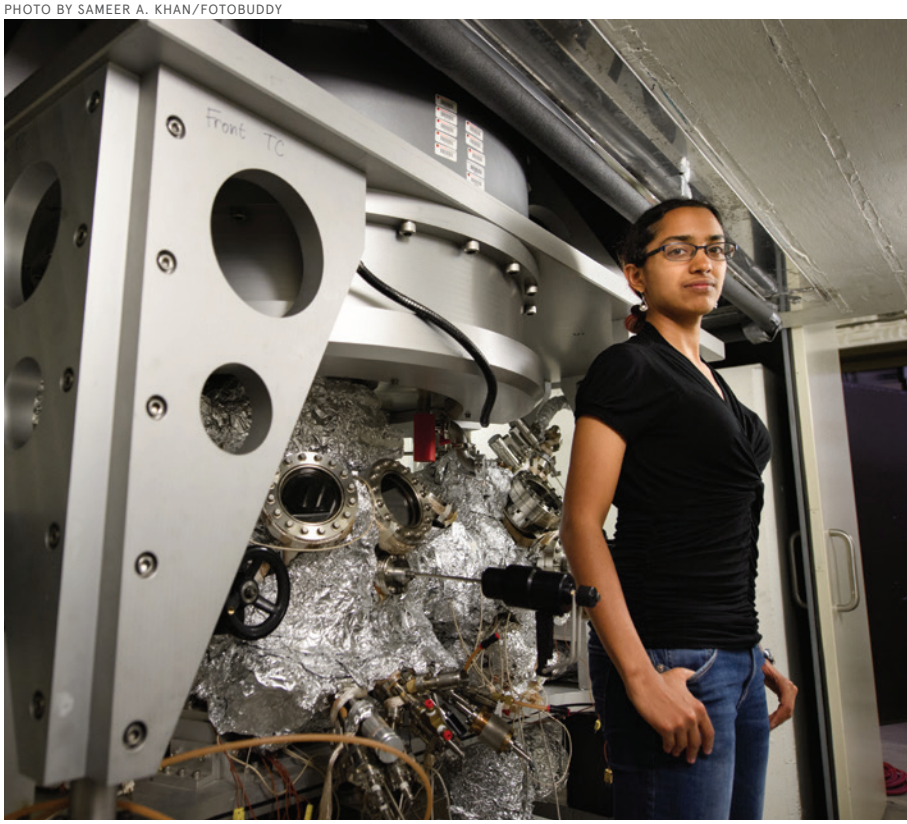
Conducting his research in this way allows Guess "to understand the type of people consuming media and what individual-level factors predict the kind of media people choose," said Kevin Munger, assistant professor of political science at Penn State University.

Adapting to the rapid change of digital media, Guess and his collaborators are now looking at technology such as video streaming and its future impact on election cycles. He is also collaborating with researchers in the study of digital literacy to help people better evaluate the news and information they see.

–By Morgan Tucker

Mallika Randeria captures
images of the quantum world

PHOTO BY SAMEER A. KHAN/FOTOBUDDY



Mallika Randeria first fell in love with quantum physics during her undergraduate years at MIT. When she took a course that required students to replicate some of the fundamental physics experiments of the past — including the 20th-century experiments that laid the groundwork for quantum mechanics — she was hooked.

"That really lit the spark," said Randeria, who recently earned her Ph.D. in physics from Princeton. "That's when I decided I definitely wanted to be an experimentalist, and not just do theory."

This focus on experimentation has allowed Randeria to peer deep into the counterintuitive world of quantum physics.

Working under the direction of Ali Yazdani, the Class of 1909 Professor of Physics, Randeria and her colleagues have, for the first time, imaged the collective behavior of electrons in a high magnetic field. In this unique environment, all the electrons begin to swirl in a distinctive elliptical orbit, a behavior never previously observed. The research is detailed in an article in the Feb. 6, 2019, *Nature*.

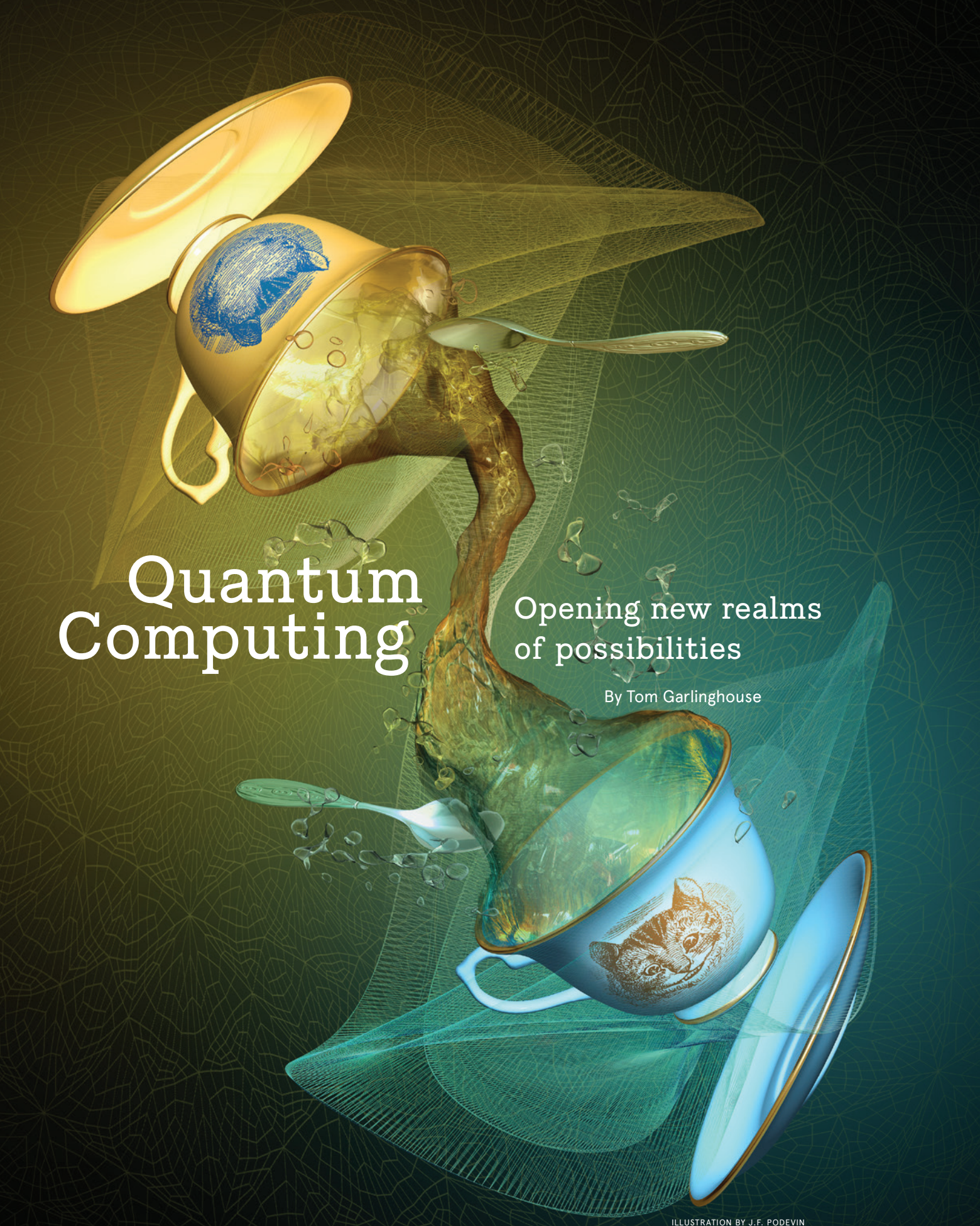
To observe this behavior, the researchers used a device called a scanning tunneling microscope, which is capable of detecting objects at the atomic scale. The experiment consisted of placing a bismuth crystal in the microscope and subjecting it to an incredibly low temperature — a few shades above absolute zero (-459 degrees Fahrenheit) — and a high magnetic field, about a thousand times the strength of a common refrigerator magnet.

What Randeria and colleagues saw was astonishing. The electrons' wave functions, which describe the probability of an electron being around an atom at any one point in time, all began to align themselves in the same direction. This is an example of collective behavior, Randeria said, because all the electrons are sensing what the other electrons are doing.

This behavior might be an example of the electrons attempting to minimize the energy costs of many electrons overlapping in different directional orbits, according to Randeria. "It becomes energetically favorable for all the electrons to point in the same direction," she said. "This experiment opened up a completely different way of studying these systems."

Randeria believes the images and behavior she and her colleagues observed could help researchers explore other behaviors in the quantum world. "The real purpose of these experiments is to push the frontiers of our understanding of physics," she said. Support for the research was provided by the Gordon and Betty Moore Foundation and the Department of Energy. **–By Tom Garlinghouse**

Mallika Randeria, who earned her Ph.D. in physics in 2019, observed how electrons behave in a collective manner — aligning themselves in the same direction due to the laws of quantum mechanics — when subjected to a high magnetic field and very low temperature.



Quantum Computing

Opening new realms of possibilities

By Tom Garlinghouse

ILLUSTRATION BY J.F. PODEVIN

Hidden beneath our everyday world — on the infinitesimal scale of atomic and subatomic particles — is a strange and elusive realm. It is a Lewis Carroll-like place where ghostly particles pop in and out of existence, swirling electrons occupy two positions at once, and objects possess dual natures — they can be both waves and particles simultaneously.

Despite the seeming irrationality of these concepts, scientists over the last 120 years have demonstrated that this realm — known as quantum mechanics — is the foundation on which our physical existence is built. It is one of the most successful theories in modern science. Without it, we would not have such marvels as atomic clocks, computers, lasers, LEDs, global positioning systems and magnetic resonance imaging, among many other innovations.

It is in the domain of information technology, however, that we might end up owing quantum mechanics our greatest debt. Researchers hope to use quantum principles to create an ultra-powerful computer that would solve problems that conventional computers cannot — from improving cybersecurity and modeling chemical reactions to formulating new drugs and making supply chains more efficient. This goal could revolutionize certain aspects of computing and open up a new world of technological possibilities.

Thanks to advances at universities and industry research centers, a handful of companies have now rolled out prototype quantum computers, but the field is still wide open on fundamental questions about the hardware, software and connections necessary for quantum technologies to fulfill their potential. Researchers at Princeton are working to chart the future of quantum computing through foundational research in their labs and through collaborations with industry partners.

"What's exciting about Princeton is that we have real expertise in both the fundamental science and the engineering," said Andrew Houck, professor of electrical engineering. "We have world leaders at every layer of this research."

The fundamental component of this new technology is the qubit, a quantum version of the classical bit that everyday computers use to represent information. A classical bit has a value of either 0 or 1, and joining these bits into strings enables computers to represent information such as letters and numbers.

Quantum bits, by contrast, can have a value of 0 or 1 at the same time. This bizarre quality stems from a quantum concept called superposition, in which an object can exist in two or more states at once. The concept, were it to be applied to everyday life, would result in the paradox known as Schrödinger's cat, in which a fictional cat is simultaneously alive and dead.

Quantum computers take advantage of the ability for qubits to exist in different states at the same time. This means that quantum computers can consider a lot more information at once, evaluating many outcomes simultaneously, thereby increasing their calculating power exponentially.

The quest for qubits

Over the last three decades, quantum researchers have come up with a handful of ways to make qubits. The heart of a qubit is typically a very small particle — such as an atom, ion or electron — that due to its tiny size exhibits quantum properties.

One of these is the superconducting qubit or transmon, which is already in use in some early-stage commercial quantum computer prototypes from IBM and Google. A transmon is a sort of artificial atom built from materials such as niobium and aluminum that, at low temperatures, can carry electrical current without resistance. These materials are patterned to form a small electrical circuit that behaves like an atom. The state of the qubit, the quantum 0 or 1, is represented by the amount of energy stored in the artificial atom.

Quantum vocabulary

Three signs you are dealing with a quantum computer

Qubits not bits
Quantum computers do calculations with quantum bits, or qubits, rather than the digital bits in traditional computers. Qubits allow quantum computers to consider previously unimaginable amounts of information.

Superposition
Quantum objects can be in more than one state at the same time, a situation depicted by Schrödinger's cat, a fictional feline that is simultaneously alive and dead. For example, a qubit can represent the values 0 and 1 simultaneously, whereas classical bits can only be either a 0 or a 1.

Entanglement
When qubits are entangled, they form a connection to each other that survives no matter the distance between them. A change to one qubit will alter its entangled twin, a finding that baffled even Einstein, who called entanglement "spooky action at a distance."

Qubit zoo

At the core of the quantum computer is the qubit, a quantum bit of information typically made from a particle so small that it exhibits quantum properties rather than obeying the classical laws of physics that govern our everyday lives. A number of types of qubits are in development:

Superconducting qubits, or transmons

Already in use in prototype computers made by Google, IBM and others, these qubits are made from superconducting electrical circuits.

Trapped atoms

Atoms trapped in place by lasers can behave as qubits. Trapped ions (charged atoms) can also act as qubits.

Silicon spin qubits

An up-and-coming technology involves trapping electrons in silicon chambers to manipulate a quantum property known as spin.

Topological qubits

Still quite early in development, quasi-particles called Majorana fermions, which exist in certain materials, have the potential for use as qubits.

Maintaining this quantum state long enough to be useful, however, is one of the major challenges for the transmon and other types of qubits. Environmental influences such as vibrations, heat or light can disrupt quantum properties. This "decoherence" can make it difficult to maintain a particle in a quantum state for even a brief length of time.

"Quantum states are incredibly fragile," Houck said. "Real progress is keeping these quantum mechanical properties 'alive' for as long as possible so that you can do the kinds of computations, sensing or communications that you want to do before all this falls apart."

To address this challenge, Houck and his team are collaborating with IBM Research to fortify the transmon by building more complex circuits that guard against decoherence. This will allow the transmon to hold a quantum state for several hundred microseconds, which is long enough to carry out many computing steps and represents a huge leap from previous qubit technology.

Another strategy for making qubits involves real atoms. Jeffrey Thompson, assistant professor of electrical engineering, cools atoms down to incredibly low temperatures and traps them in a vacuum chamber. Once isolated, the researchers can manipulate an individual atom with tightly focused laser beams called optical tweezers. The researchers can then use additional laser signals to set the trapped atom's energy levels to represent quantum 0 or 1 states.

"Atoms make very good qubits," Thompson said. "They are actually easy to work with, and it's very easy to see a single atom using laser light."

Still another type of qubit relies on electrons, or more specifically, an inherent quantum property of electrons known as spin. Spin describes the electron's angular momentum and is sometimes likened to the twirling movement of a top, but it is also analogous to magnetism because, like a magnet, an electron's spin can point either downward or upward, representing the values of 0 and 1.

Stephen Lyon, professor of electrical engineering, is one of the researchers exploring ways to keep spin qubits in superposition for relatively long periods. His team sends microwave pulses through a highly purified type of silicon, called silicon-28, to coordinate the spins of millions of electrons. The researchers have shown that they can keep spin qubits in superposition for up to 10 seconds, a lengthy duration in the quantum realm.

For quantum computing to achieve its full potential, qubits will not only need to keep their quantum states, but they will also need to share information with each other. They do this via a quantum property called entanglement.

Like superposition, entanglement is a baffling — but fundamental — quantum concept. It describes how two particles can act in concert. After two or more quantum particles interact, they can retain their connection or interdependence. If one qubit acts in a certain way, its entangled twin will act in the same way, no matter the distance that divides them. They can be millions of miles away but still act in perfect unison. This counterintuitive notion, which has survived numerous challenges since its discovery in the 1930s, led Albert Einstein to label entanglement as "spooky action at a distance."

By entangling qubits, researchers can build quantum circuits that can do complex calculations. Jason Petta, the Eugene Higgins Professor of Physics, is working on this challenge for silicon-based spin qubits. Single spins can have a lifetime of up to one minute. Silicon spin qubits could prove less expensive and easier to manufacture than other types of qubits, and although they are not as far along in development as transmons, they are quickly catching up due to recent advances.

Petta's team is devising ways to transfer the information coded in the electron's spin from one qubit to another — getting electrons to, as

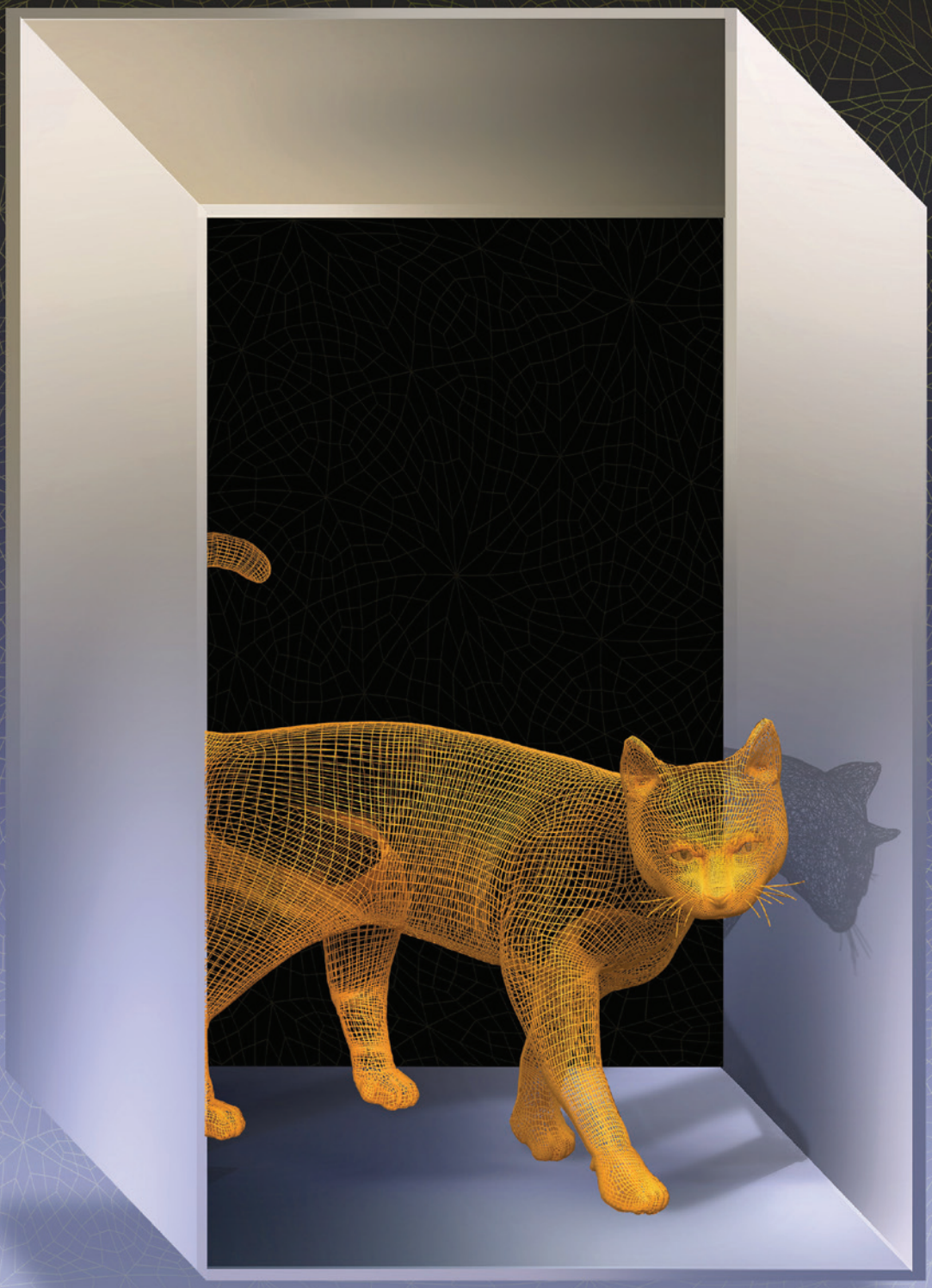


ILLUSTRATION BY J.F. PODEVIN

he calls it, "talk to each other." They build qubits by confining electrons in tiny silicon chambers called quantum dots. The researchers can then apply a strong magnetic field to the dots to coax them to transfer their quantum information to particles of light, or photons, which act as messengers to carry the information to other quantum dots located nearby. This strategy has already been used to entangle superconducting qubits, and the Petta group showed that this approach also works for spin-based qubits.

"It's like putting an electron and a photon in the same room," Petta said. "You can transfer some of the spin properties to the photon, which is flying around the room, and then use the photon to transmit information to another spin on the opposite side of the room."

The variety of ways of producing qubits underscores the state of quantum computing today. One of the more long-term strategies is to make qubits from Majorana fermions, which are particle-like objects that form under specific conditions. Predicted nearly a century ago, these quasi-particles were recently observed in experiments led by Ali Yazdani, the Class of 1909 Professor of Physics. The properties of these quasi-particles stem from a branch of mathematics called topology, which describes how objects can be bent or stretched without losing their inherent properties. This property could give these topological qubits better protection from decoherence.

Which qubit will ultimately form the basis of a future quantum computing industry? This is a quickly developing field with everyone hesitant to predict which qubit will prove the best, according to Lyon. "There are all these different technologies," he said, "and the simple matter is we don't know which one is going to work best."

Introducing the Princeton Quantum Initiative

In September 2019, the University announced the creation of the Princeton Quantum Initiative to foster exploration and education across the spectrum from fundamental quantum research to applications in areas such as computing, sensors and communications.

The initiative comes at a time of national momentum for quantum sciences. In 2018, the federal government established the National Quantum Initiative to energize research and training in quantum information science and technology. The Princeton initiative will offer fellowships for graduate students and postdoctoral researchers, and research and educational opportunities for undergraduates.

Over 30 faculty members, drawn from the departments of electrical engineering, physics, chemistry, computer science, and mechanical and aerospace engineering, will participate in the new program. The initiative will enable new research collaborations across campus and with other universities and industry.

The initiative's inaugural director is Andrew Houck, professor of electrical engineering. "We have an incredible collection of experts in their respective disciplines," Houck said, "and the Princeton Quantum Initiative gives us an entity that brings everyone together to accelerate the pace of discovery."

The quantum internet

Creating well-functioning qubits is only one aspect of quantum computing. An equally important goal is the creation of a quantum information network — a quantum internet — that will be more secure than today's internet. Nathalie de Leon, assistant professor of electrical engineering, is testing the viability of synthetic diamonds as devices that store and transmit information from one place to the next. Although a diamond may look clear and flawless, a close examination reveals something very different.

"If you take a diamond and pull it out of the ground and look at it, you'll notice all these little defects," de Leon said. These defects give diamonds their color, but it turns out that they also can store and transmit information.

De Leon and her colleagues figured out that by replacing two carbon atoms with a silicon atom, this particular flaw in diamonds can act as a perfect receptacle to catch a photon. Photons already carry information via the optical fibers of today's internet, and they can also be used to carry quantum information.

De Leon and her team are working to transmit quantum information from photons to electron spins, where further fine-tuning can prolong the quantum state by keeping electron spins in the proper orientation.

Quantum entanglement ensures that this new kind of internet is secure against hackers. Any attempt to eavesdrop on the transmission will perturb its state. By comparing the transmitted photon to its entangled twin, the receiver can tell if an eavesdropper has disrupted the transmission. "As long as the laws of physics are correct, our channel is secure," de Leon said.

Quantum architecture

A handful of quantum computers are now in operation, and a few are available for experimentation through the cloud, but they are still

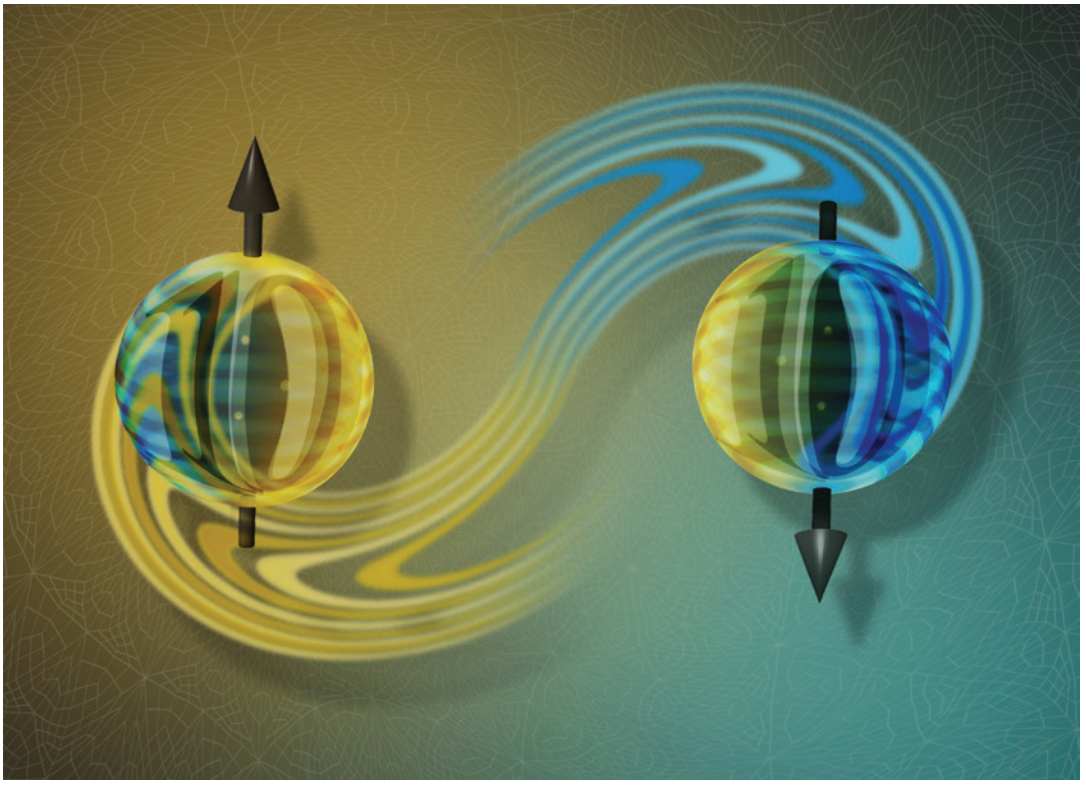


ILLUSTRATION BY J.F. PODEVIN

works in progress. For one thing, these computers have qubits in the hundreds, whereas several thousands or even millions of qubits are needed for hard problems. Another challenge is that qubits are difficult to manufacture, and some of the qubits won't behave as expected, requiring researchers to add extra qubits for quantum error correction.

And although quantum computers will be capable of addressing problems that we currently have no way of solving, they likely will not replace our familiar computers for everyday tasks. "We're not going to have a quantum computer in my laptop or phone," said Margaret Martonosi, the Hugh Trumbull Adams '35 Professor of Computer Science. "It's a fairly unique and narrow set of algorithms where quantum computers have an advantage over classical computers."

One of the unique and narrow algorithms, however, could crack the encryption codes in use today to protect credit card transactions on the internet. The potential misuse of quantum power is driving the search for new quantum cryptography methods.

Martonosi is one of the pioneers thinking about how quantum computers will make the transition from laboratory prototypes into practical, functioning devices. This area of research is called computer architecture, and involves everything from how a quantum computer would interface with existing technologies to what types of software would be compatible with quantum systems.

In today's computers, software plays the role of coordinating and translating bits into calculations and results. The same applies to quantum computing. Martonosi and her team are developing programs called compilers that read and translate high-level programming languages down to the level of the computer's qubits. "Our compiler uses advanced optimization techniques to exploit the better-behaving qubits," she said.

She is also developing software to explore which algorithms work best with different kinds of qubits, and is optimistic about recent developments in the field. "Every new qubit in a quantum computer, if it behaved in an ideal way, would actually double the capability of a quantum computer," Martonosi said. "This would be faster and better than the largest supercomputer on Earth. That will be an important milestone."

Although truly powerful quantum computers with millions of qubits are still years away, the technologies for creating this advantage are edging closer. Our knowledge has progressed to the point where rather than simply studying quantum mechanics, we are on the verge of unlocking vast new capabilities utilizing its bizarre, ghostly concepts. ›

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

The Torture Letters

Laurence Ralph explores Chicago's dark history

By Catherine Zandonella

On a hot day in 2004, Laurence Ralph, recently arrived in Chicago to attend graduate school, stood on the corner of Lawndale Avenue and Cermak Road.

Two young teens, a boy and a girl dressed in white shirts and khaki pants, knelt on the sidewalk while six police officers emptied the contents of their book bags onto the concrete. For 26 minutes and 43 seconds, Ralph watched transfixed, wishing he were a family member or friend so that he could intervene to ask if the students were OK.

He was also reliving a memory from his own childhood, when shortly after moving from Baltimore to suburban Maryland he went with his two older brothers to the mall. A plainclothes officer followed them from store to store, finally stopping them near a railing on the second floor overlooking the food court, where the officer frisked the older boys.

"I could feel myself in my own skin unlike ever before," Ralph writes of that moment in his new book, *The Torture Letters: Reckoning with Police Violence* (University of Chicago Press, 2020). "Adrenaline spiked my senses. All of a sudden I felt hair stand up from the follicles on my forearms. I could catch the sound of people chattering below me. I could smell fried potato wedges from the Boardwalk Café on the floor below, where a crowd of people gathered, eyes upward, watching the commotion against the second-story railing. I had been in that restaurant, eating those thick fries, just a few hours earlier. I wanted desperately to return to that moment."

Observing the sidewalk scene in 2004, Ralph was relieved when the police finally released the Chicago teens, just as he had been when the mall's officer finally released his brothers. "I also felt a familiar combination of cowardice, anger, guilt, frustration — and yes, fear."

This episode and the memories spurred Ralph, now a professor of anthropology at Princeton, to focus his research on police violence against black and brown people, and particularly on a dark chapter in Chicago history: the torture of people of color at the hands of police from the mid-1970s to the early 2000s.

In *The Torture Letters*, Ralph details the appalling brutality of officers at Chicago's Area 2 precinct. There, officers abused numerous suspects, sometimes wresting false confessions that resulted in death penalty sentences.

Delving into letters, court records, testimonies and other sources as part of his research, Ralph soon realized that torture was not just the work of a few rogue cops. Aimed primarily at black males, the cruelty involved generations of police officers and was an open secret, shared with officials as high as Cook County State's Attorney Richard M. Daley, who would later become mayor of Chicago.

As Ralph learned more, he came to realize that his investigation was less about the violence itself and more about why, despite widespread awareness of the problem, so little was done. "Why have so many powerful and influential people in Chicago been unwilling to publicly acknowledge acts of extrajudicial police force such as torture?" Ralph asks in the book's preface.

Public allegations of torture by Chicago police officers first surfaced in 1982, after a man named Andrew Wilson was arrested for murdering two police officers during a traffic stop. Brought to the station after a days-long manhunt, Wilson confessed to the crime. But the worst was yet to come.

In the ensuing hours, the officers didn't merely beat Wilson. They connected his ears and nostrils to a contraption that administered electric shocks and pushed his chest against a hot radiator. Although his injuries were documented at the Cook County Jail and a report was sent to Chicago's chief of police, no investigation was launched.

Wilson received a lengthy sentence, but later filed a lawsuit from behind prison walls with the help of a legal aid firm. What happened next was surprising. In two separate trials, despite photos, medical reports and other evidence, jurors could not unanimously agree that Wilson

had been tortured. The jury had little sympathy for a confessed cop-killer. The first trial ended in a hung jury. In the words of one juror in Wilson's second trial, "[The officers] were just acting out their anger toward this guy."

That remark and others like it awakened Ralph to one of the ways in which many witnesses, including precinct officers who did not participate in torture but also did not report it, justified their lack of action: the victim deserved what he got.

Ralph explores this notion — that violence is justifiable depending on the identity of the victim — as problematic not just from a moral stance but also because of America's history of enslaving African Americans. For hundreds of years, Ralph writes, Americans were conditioned to think of blacks as inherently prone to criminal acts — since running for one's freedom was a crime — and violent in nature, hence the need for chains and beatings. "The tendency of white Americans to view blacks as criminals," Ralph writes, "helps us better understand the phenomenon of police torture."

Although Wilson was denied justice, the publicity around the trial spurred an anonymous whistleblower called "Deep Badge" to come forward, leading eventually to the identification of 50 Area 2 police officers involved in torture. Between 1972 and 1991, roughly 125 African American suspects were tortured by Chicago police.

In 2009, the state of Illinois set up a committee to investigate torture claims, which today number in the 400s. The city has paid millions in settlements both to victims innocent of any crime and those like Andrew Wilson, who were guilty. (His settlement money went to his victims' families.)

But settlements will never be enough until the principle of "innocent until proven guilty" is extended to blacks, Ralph writes. Deeply held prejudices cause police officers to escalate too quickly toward use of force even in everyday interactions. "By hating and condemning people, we actually make them more vulnerable for torture," Ralph writes.

This link between racism and torture is evident not only in Chicago but also around the United States and the world, according to Ralph. In his book, he explores links between torture in Chicago and at the Guantánamo Bay military prison. These links are both metaphorical and tangible: One of the officers at the U.S. military prison in Cuba was on leave from the Chicago police force where he had been a torturer.

Ralph also talked to civil rights leaders who define the torture of black people as a type of genocide. At first torture and genocide seem nothing alike: torture terrorizes individuals, while genocide annihilates populations. But Ralph came to understand the connection: Blacks are one of the most marginalized groups in American society, and therefore are at greater risk of being tortured.

During his time as a graduate student, Ralph recorded Chicago's chilling history with the meticulousness required of academic research, but he kept coming back to the image of the two black teenagers kneeling on the hot pavement. He was living in West Side Chicago where every friend and neighbor could recount the

> "I could not help but think long and hard about these residents' concerns. I did not want what they told me to just be beneficial to other scholars who theorized torture for a living."
>
> **Laurence Ralph**
> Professor of Anthropology

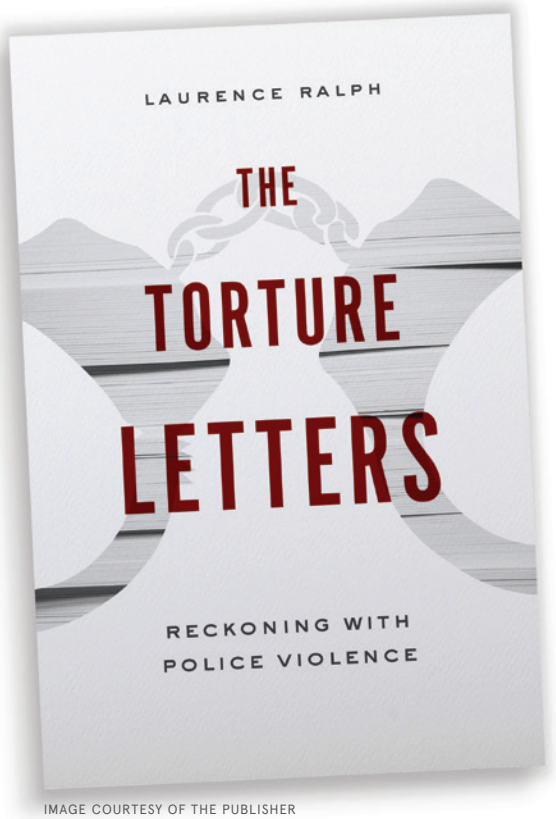


IMAGE COURTESY OF THE PUBLISHER

In Laurence Ralph's new book, "The Torture Letters: Reckoning with Police Violence" (University of Chicago Press, 2020), he explores the brutal treatment of African Americans while in the custody of Chicago police officers and its lasting legacy.

story of a police encounter that was frustrating, humiliating or terrifying.

"I could not help but think long and hard about these residents' concerns," Ralph writes. "I did not want what they told me to just be beneficial to other scholars who theorized torture for a living. I wanted to honor what I had learned from them by embracing their challenge to speak to multiple audiences."

Breaking with scholarly anthropological tradition, Ralph decided to write his book as a series of open letters to friends and neighbors, to torture victims, perpetrators and witnesses, and to officials both past and present who have the power to stop the torture.

One is "An Open Letter to the Boy and Girl with Matching Airbrushed Book Bags on the Corner of Lawndale Avenue and Cermak Road."

"By writing to this larger group," Ralph writes in the letter, "I hope that my silence that day in 2004 will be replaced by a loud voice that insists on my apology to you for not stepping forward back then. Through my letters, I'll also be talking to the big, beautiful community of kids of color who still have to reckon with the same institutional racism that you faced on that day."

Ralph's book is ultimately a missive to society, asking us to challenge our beliefs — that violence is justified if the victim is guilty, and that people with black skin are more likely to be criminals or are less deserving of the police's respect.

"Fear of 'the other' made it possible for torture to become a routine part of interrogating criminal suspects in certain Chicago precincts," Ralph writes in the book's last letter, directed to the reader. "That same fear allowed the tentacles of torture to reach the shores of Guantánamo Bay."

The letter continues: "With this contraption splayed wide open, let us all finally see how understanding police torture — and taking concrete steps to prevent it — requires us to dismantle the fear at the root of this pernicious American practice." ›

Fragile Fragments

Marina Rustow unpacks daily life in medieval Egypt

By Jamie Saxon

Imagine what the stuff of everyday life — personal letters, the deed of a house, a shop owner's inventory records — might look like in medieval times. Since the late 1990s, historian Marina Rustow has immersed herself in a unique cache of such documents hidden away for centuries in an Egyptian synagogue.

This collection, known as the Cairo Geniza, comprises more than 400,000 fragments of legal documents, letters and literary materials, going back to about the year 870, that were consigned to a hiding place or storeroom (in Hebrew, "geniza") in the medieval Ben Ezra Synagogue in the old city of Cairo.

In that era, damaged or worn-out religious texts and unneeded old documents could not be thrown away if they contained the name of God. In the mild Egyptian climate, the centuries-old texts were preserved. These items, which came to the attention of dealers and collectors in the 1890s, span more than a millennium and now reside in about 60 library and private collections around the world.

The Cairo Geniza is "a mirror of the society," said Rustow, the Khedouri A. Zilkha Professor of Jewish Civilization in the Near East and a professor of Near Eastern studies and history. The documents offer insight into the everyday lives of Jews in medieval Egypt and beyond, much like the documentary papyri of Roman and Islamic Egypt, as well as Arabic paper documents of Egyptian Muslims and Christians during the Middle Ages.

"People had mainly been interested in what historians call literary texts — such as the Bible and Rabbinic literature," Rustow said. "Nobody paid much attention to the other 10% of it, the documents."

That is, until 1948, when the scholar S.D. Goitein realized that there was a whole world to be discovered from the letters, marriage contracts, bills of sale, recipes, personal checks, descriptions of houses and real estate documents, said Rustow, who received a 2015 MacArthur Fellowship for her research on the Geniza texts. She uses Goitein's five-volume work, *A Mediterranean Society: The Jewish Communities of the Arab World as Portrayed in the Documents of the Cairo Geniza*, when teaching classes.

Since 1985, the Department of Near Eastern Studies has been the home of the Princeton Geniza Lab — a collaborative space devoted to making the documents accessible to the scholarly world and the general public. Rustow heads the lab, which hosts a searchable database of Geniza texts transcribed from the originals.

Since coming to Princeton in 2015, Rustow has expanded her collaboration with Cairo Geniza scholars around the world, while bringing graduate and undergraduate students — both in the classroom and through independent work — into this fascinating world.

The inadvertent historian

By her own admission, Rustow, a native of New York City, came to history "very, very late." History was her worst subject in high school, where she focused on accelerated math and science classes. She earned a bachelor's degree in literature from Yale University, and didn't take a single history class.

Her early love of language, however, foreshadowed what would become a scholarly focus that requires multiple languages. At Nightingale-Bamford, the all-girls' school in

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

From fragments of marriage contracts, bills of sale, recipes and other papers hidden away for centuries in a Cairo synagogue, historian Marina Rustow documents the everyday lives of Jews in medieval Egypt.

The last letter to noted Jewish philosopher Moses Maimonides from his brother David, a long-distance trader, written in Judeo-Arabic in 1170. David relates how he missed an ill-fated caravan from Cairo to Sudan in which the travelers were robbed and killed. David himself died on a sea voyage shortly thereafter. (Fragments reproduced by kind permission of the Syndics of Cambridge University Library.)

Manhattan she attended before high school, she began studying Latin in sixth grade. "Latin taught me a certain kind of rigor about textual sources and never to trust your memory about what a word might mean because there are so many nuances," Rustow said.

Between college and graduate school, she worked as an editor and journalist in San Francisco. Three thousand miles from the Upper West Side of her childhood — "in those days, the epicenter of Jewishness but not necessarily of Judaism" — she realized that if she had any questions about Judaism, she would have to answer them herself. She moved to Jerusalem for two years, where she learned Hebrew.

When it came time to apply to graduate school, Rustow intended to study English literature. "Once I actually started looking into programs, I realized all I wanted to study was Rabbinic literature," Rustow said. In 1994, she entered Columbia University to study with David Weiss Halivni, one of the pioneers in dissecting Rabbinic texts to discover how they had come into being chronologically. In her fourth semester, her trajectory changed again, this time toward history, when she took a seminar with Yosef Hayim Yerushalmi, one of the pioneers in using Rabbinic literature to write history.

"I am forever grateful to him because he knew that I was a historian before I did," Rustow said.

Yerushalmi encouraged her to specialize in Jews in the Islamic world in the Middle Ages. "An estimated 90% of Jews lived in the Islamic world in the Middle Ages," Rustow said. "So, if you don't have a student who's studied that, you're missing a big chunk of Jewish history."

With Yerushalmi's guidance, Rustow became that student. She began studying Arabic, and deep-diving into the Cairo Geniza. "I was hooked," she said.

Apart from medieval manuscript fragments, Rustow is interested in the classical musical traditions of the Middle East, especially theory and performance practice in the Arab, Ottoman, Persian, Andalusi and Iraqi traditions. She plays oud, buzuq and classical piano.

From 11th-century 'fast food' to family tussles

Amidst thousands of paper fragments, Rustow has uncovered myriad examples of medieval life that are remarkably similar to modern times. She likes to tell the story of what she describes as metal take-out containers. "They appear in things like merchants' inventories or dowry lists for marriage contracts," she said. By studying the urban architecture of the period, she knew that most people didn't cook at home.

"Essentially, people got their warm food in the bazaar," she said. "Just as the city of Cairo today is the epicenter of food delivery — because of the dust, diesel fumes and traffic, everybody gets things delivered — people in the 11th century went to the market to get their hot food or 'fast food.'"

The documents also reveal a social history that's not so different from family life today. For example, a letter from a father to his daughter reflects "divorced parents taking digs at each other and guilt-tripping their kid, putting her in the middle — and yet this is happening in scribal handwriting," Rustow said. "It's a familiar and unfamiliar society at the same time and that's what's so addictive about it."

Bringing undergraduates into 'the scholarly ecosystem'

Rustow's students have a unique opportunity to examine original fragments. The world's second largest Cairo Geniza collection, at the Jewish Theological Seminary (JTS) in New York City, is being housed temporarily at Princeton while JTS rebuilds its library. The collection includes some 40,000 handwritten text leaves and documents.

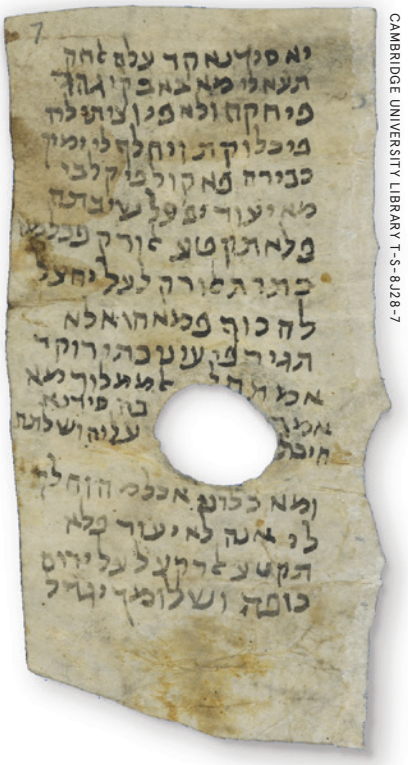
As director of the Princeton Geniza Lab, Rustow has made it a priority to incorporate undergraduates "into the scholarly ecosystem in the same way that you have undergrads in a biology lab mixing agar gels and watching research happen in real time," she said. "Undergrads can

do serious primary research even if they don't have the language skills for the Geniza, though here at Princeton, I've been pleasantly surprised to see how many of them do."

Creating databases of Geniza documents is one of the tasks in which undergraduates have contributed to the field. "They can make a database of 85 documents that mention wine, for example," Rustow said. "Then they determine which documents haven't been translated and kick them upstairs to graduate students and specialists at the Princeton Geniza Lab to translate, who then kick the translated documents back to the undergraduate students, who now have a set of unpublished sources for their junior papers and senior theses," she said.

Rustow said she thrives on what she learns from students — in the classroom and the Princeton Geniza Lab. "I want to show them that I don't know everything and that in fact what keeps me in this game is what [Italian historian] Carlo Ginzburg calls 'the euphoria of ignorance.' It's precisely when I don't know something that I'm most excited — and that's when they should be excited too."

The fact that the documents are literally fragments makes it essential to collaborate. "I could be holding onto the bottom half of a piece of a paper that my colleague in Oxford is working on the top of and we'll never know unless we talk to each other," she said. "When you're working on a fragmentary corpus or an archive of 400 letters that was broken apart and is now in 60 different collections, how can you not collaborate?"



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In this undated letter, a teacher complains to the parents of a student. The parents' reply is on the other side of the document.

The Geniza Lab's online database makes these collaborations easier than ever, but the irony of using digital technology to study ancient paper is not lost on Rustow. Paradoxically, she said, it's precisely as old texts have been digitized that researchers have started paying attention to them as physical objects. For example, paper in the medieval Islamic world was made from used cloth, usually linen and hemp, which opens questions about the history of textiles, including clothing, and of the flax trade, which was the backbone of the Egyptian economy in the Middle Ages. "There hasn't been a lot of work done on the material composition of Geniza paper," Rustow said. "That's an area that's ripe for collaboration between humanists and scientists, a collaboration I'd like to see happen at Princeton." ›

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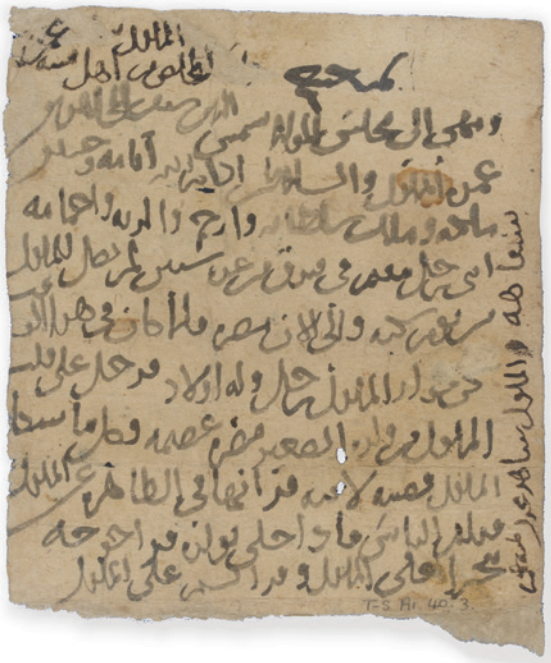
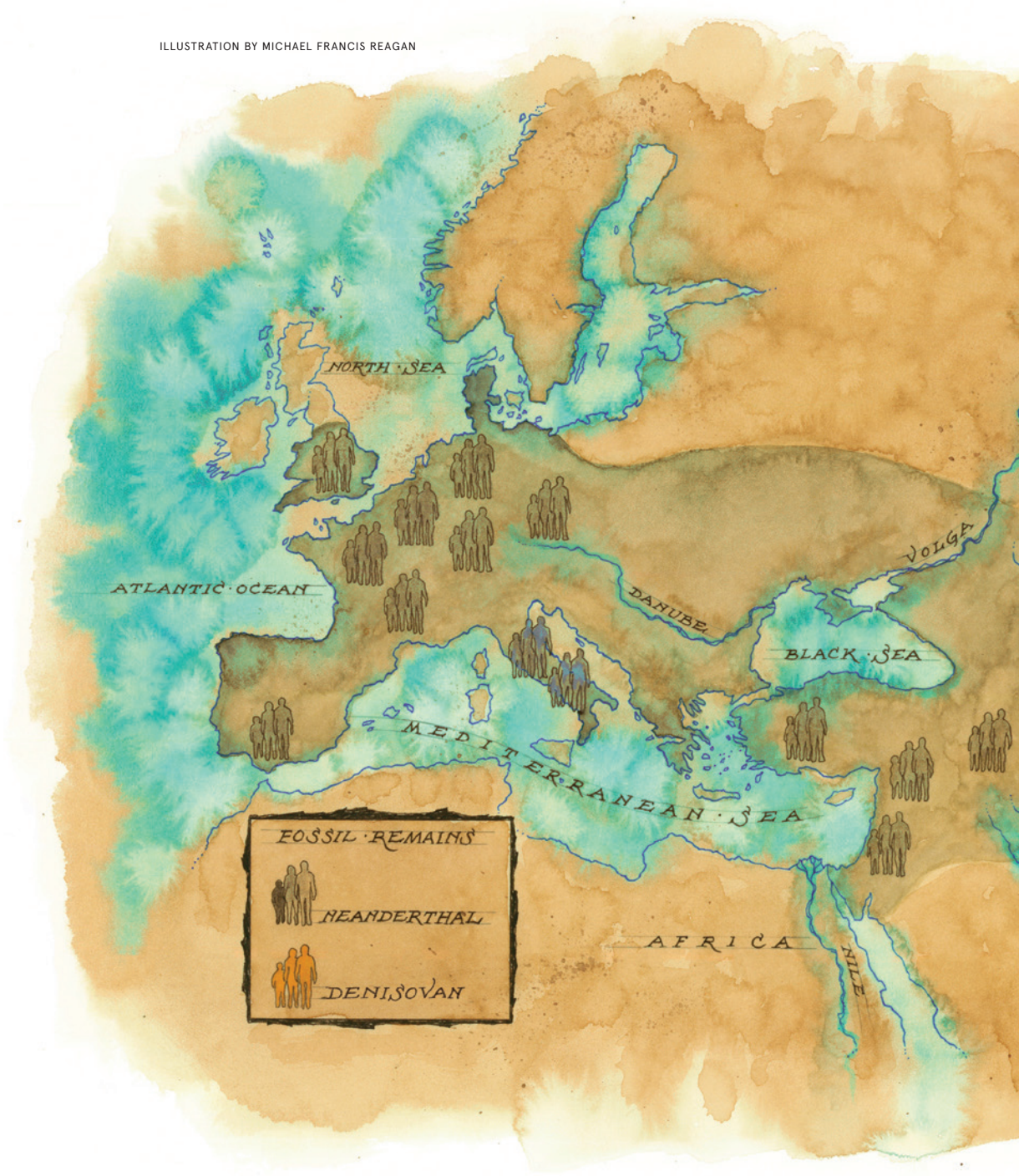


A petition to an Egyptian sultan complaining about the unruly son of a neighbor dates from the 12th-13th century. The boy harassed the petitioner's family and bit his wife to the point of injury.

ILLUSTRATION BY MICHAEL FRANCIS REAGAN



Origin Story

Rewriting human history through our DNA

By Tom Garlinghouse

For most of our evolutionary history — for most of the time anatomically modern humans have been on Earth — we've shared the planet with other species of humans. It's only been in the last 30,000 years, the mere blink of an evolutionary eye, that modern humans have occupied the planet as the sole representative of the hominin lineage.

But we carry evidence of these other species with us. Lurking within our genome are traces of genetic material from a variety of ancient humans that no longer exist. These traces reveal a long history of intermingling, as our direct ancestors encountered — and mated with — archaic humans. As we use increasingly complex technologies to study these genetic connec-

Fossil evidence illustrates the spread of two long-extinct hominin species, Neanderthals and Denisovans. Modern humans carry genes from these species, indicating that our direct ancestors encountered and mated with archaic humans.

tions, we are learning not only about these extinct humans but also about the larger picture of how we evolved as a species.

Joshua Akey, a professor in the Lewis-Sigler Institute for Integrative Genomics, is spearheading efforts to understand this larger picture. He calls his research method genetic archaeology, and it's transforming how we're learning about our past. "We can excavate different types of humans not from dirt and fossils but directly from DNA," he said.

Combining his expertise in biology and Darwinian evolution with computational and statistical methods, Akey studies the genetic connections between modern humans and two species of extinct hominins: Neanderthals, the classical "cave men" of paleoanthropology; and Denisovans, a recently discovered archaic human. Akey's research divulges a complex history of the intermixing of early humans, indicative of several millennia of population movements across the globe.

"There's often a divide between the researchers who go out and collect exotic samples and the researchers who do really creative theory and data analysis, and he's done both," said Kelley Harris, a former colleague of Akey's who is now an assistant professor of genome sciences at the University of Washington.

Like many of us, Akey has long been interested in how the human species evolved. "People want to learn about their past," he said. "But

even more than that, we want to know what it means to be human."

This curiosity followed Akey throughout his schooling. During his graduate work at the University of Texas Health Science Center at Houston in the late 1990s, he looked at how contemporary humans in different parts of the world were genetically related to one another, and used early gene sequencing methods to try to understand these relationships.

Gene sequencers are devices that determine the order of the four chemical bases (A, T, C and G) that make up the DNA molecule. By determining the order of these bases, analysts can identify the genetic information encoded in a strand of DNA.

Since the 1990s, however, gene sequencing technology has progressed dramatically. A new technology known as next-generation sequencing came into use around 2010 and allowed researchers to study a very large number of genetic sequences in the human genome. It took 10 years to sequence the first human genome, but these new machines get whole genome sequence data from thousands of individuals in only a matter of hours. "When next-generation sequencing technology started to become the dominant force in genetics," Akey said, "that completely changed the entire field. It's hard to overstate how dramatic this technology has been."

The scale of the data that now can be analyzed has allowed researchers to address a whole slew of new questions that would not have been possible with the previous technology.

One of these questions is the relationship between modern humans and archaic humans, such as Neanderthals. In fact, this question fostered a vigorous debate about whether modern humans carried genes from Neanderthals. For many years, the opinions of researchers — both pro and con — ticked back and forth like a metronome.

Gradually, however, a few researchers — including geneticists Svante Pääbo of the Max Planck Institute in Germany and his colleague Richard (Ed) Green of the University of California-Santa Cruz — began to demonstrate strong evidence that, indeed, there had been gene flow from Neanderthals to modern humans. In a 2010 paper, these researchers estimated that people of non-African ancestry had about 2% Neanderthal ancestry.

Neanderthals lived in a wide geographical swath across Europe, the Near East and Central Asia before dying out around 30,000 years ago. They lived alongside anatomically modern humans, who evolved in Africa some 200,000 years ago. The archaeological record shows that Neanderthals were adept at making stone tools and developed a number of physical traits that uniquely adapted them to cold, dark climates, such as broad noses, thick body hair and large eyes.

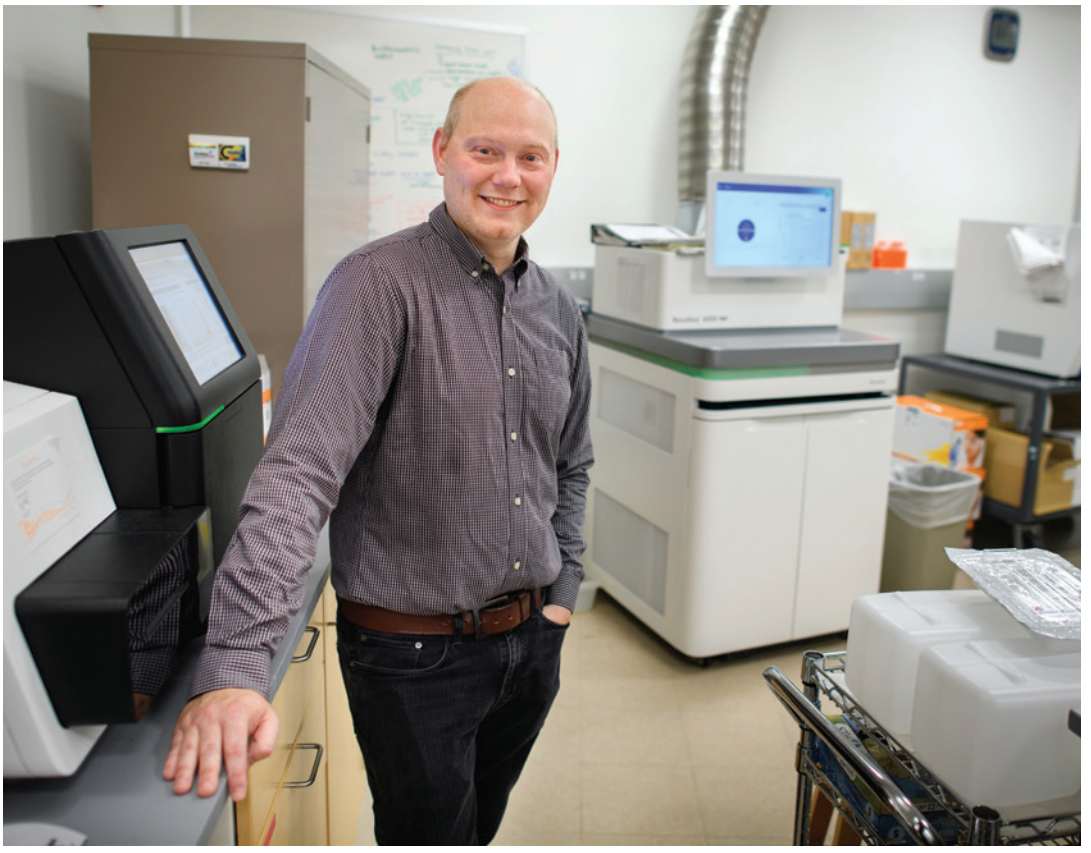
Following on the heels of Pääbo and Green's Neanderthal research, Akey and a colleague, Benjamin Vernot, published a paper in *Science* looking at recovering Neanderthal sequences from the genome of modern humans. Geneticist David Reich of Harvard University published a similar paper in *Nature*, and, together, the two papers provided the first data employing the modern genome to investigate our link with Neanderthals.

Using the genetic variation in contemporary populations to learn about things that happened in the past involves scrutinizing the modern human genome for gene sequences that display traits expected to have been inherited from a different type of human. Akey and his colleagues then take those sequences and compare them to the Neanderthal genome, looking for a match.

Using this technique, Akey has been able to uncover a rich human legacy of genetic interconnections on a scale previously unconceived. As stated, while the available evidence suggests that non-Africans carry about 2% of Neanderthal genes, Africans, who were once believed not to have any connections with Neanderthals, actually have approximately 0.5% Neanderthal genes. Researchers have further discovered that the Neanderthal genome has contributed to several diseases seen in modern human populations, such as diabetes, arthritis and celiac disease. By the same token, some genes inherited from Neanderthals have proven beneficial or neutral, such as genes for hair and skin color, sleep patterns and even mood.

Akey has also discovered genetic fingerprints that suggest our human ancestry contains species about which we know nothing or very little. The Denisovans are a case in point. An archaic form of human, they coexisted with anatomically modern humans and Neanderthals and interbred with both before going extinct. The first evidence of their existence came in 2008 when a finger bone was discovered in Denisova Cave in the remote Altai Mountains of southern Siberia. At first the bone was assumed to be Neanderthal because the cave contained evi-

PHOTO BY SAMEER A. KHAN/FOTOBUDDY



Joshua Akey is a leader in the field of genetic archaeology, the use of genes to explore connections between modern humans and now-extinct hominins. With modern gene-sequencing technologies, researchers like Akey are revealing new information about archaic human lineages as well as our own evolutionary history.

dence of these species. Consequently, it sat in a museum drawer in Leipzig, Germany, for many years before it was analyzed. But when it was, the researchers were dumbfounded. It wasn't a Neanderthal — it was a hitherto unknown type of ancient human. "The Denisovans are the first species ever identified directly from their DNA and not from fossil data," Akey said.

Since that time, continued genetic work — much of it conducted by Akey and his colleagues — has established that the closest living relatives of Denisovans are modern Melanesians, the inhabitants of the Melanesian islands of the western Pacific — places such as New Guinea, Vanuatu, the Solomon Islands and Fiji. These populations carry between 4% and 6% of Denisovan genes, though they also carry Neanderthal genes.

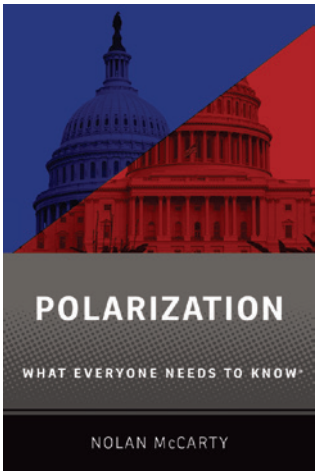
Examples like this highlight one of the main features of our human lineage, Akey said, that admixture has been a defining feature of our history. "Throughout human history there's always been admixture," Akey said. "Populations split and they come back together."

While there remains a lot of debate about the Denisovans, Akey believes they most likely were closely related to Neanderthals, perhaps an eastern version who split off from the latter sometime around 300,000 or 400,000 years ago. Recently, genetic analysis of fossils from Denisova Cave has uncovered evidence of an offspring between a Neanderthal woman and a Denisovan male. The offspring was a female who lived approximately 90,000 years ago. By looking at this genetic trail, Akey and other researchers have been able to piece together a fascinating story of human evolution — one that is promising to rewrite our understanding of early human origins.

"Our genomes are a mosaic of different histories," he said. "They are an amazing historical record of things that happened."

But there's so much more to discover, Akey said. "Even though we have sequenced probably 100,000 genomes already, and we have pretty sophisticated tools for looking at that variation, the more we think about how to interpret genetic variation, the more we find these hidden stories in our DNA," he said. ›

Books



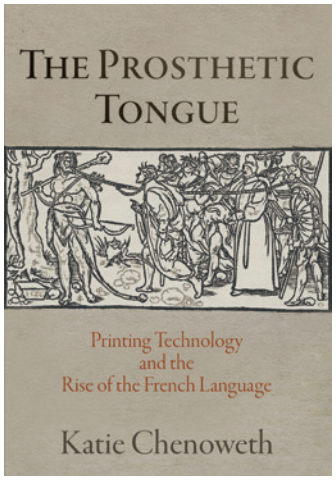
Polarization:

What Everyone Needs to Know

Oxford University Press, July 2019

Nolan McCarty, the Susan Dod Brown Professor of Politics and Public Affairs

The 2016 election of Donald J. Trump invoked a time for reflection about the state of American politics and its deep divisions. While the current political climate seems to suggest that extreme views are becoming more popular, McCarty argues that, contrary to popular belief, the 2016 election was a natural outgrowth of 40 years of polarized politics, rather than a significant break with the past. A concise overview of a complex and crucial topic in U.S. politics, this book is for anyone wanting to understand how to repair the cracks in our system.



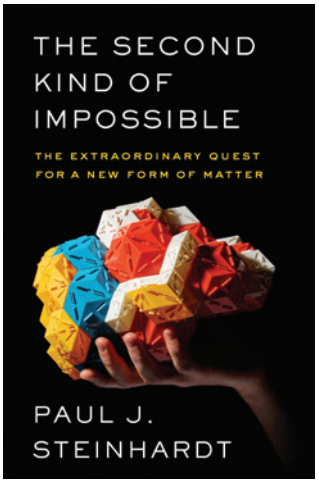
The Prosthetic Tongue:

Printing Technology and the Rise of the French Language

University of Pennsylvania Press, November 2019

Katie Chenoweth, associate professor of French and Italian

Of all the cultural "revolutions" brought about by the development of printing technology during the 16th century, perhaps the most remarkable but least understood is the purported rise of European vernacular languages. Chenoweth explores the relationship between printing and the vernacular as it took shape in 16th-century France, when the French language underwent a remarkable transformation, as printers and writers began to reimagine their mother tongue as mechanically reproducible. This was, Chenoweth argues, a veritable "new media" moment. No less than the paper book issuing from 16th-century printing presses, the modern French language is a product of the age of mechanical reproduction.



The Second Kind of Impossible:

The Extraordinary Quest for a New Form of Matter

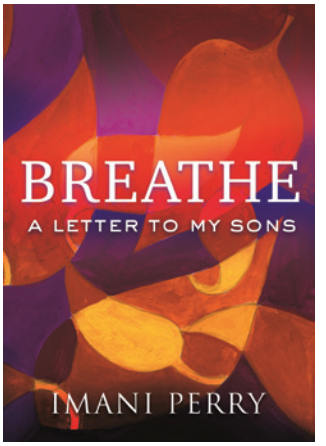
Simon & Schuster, January 2019

Paul Steinhardt, the Albert Einstein Professor in Science and professor of physics

It begins with a curious geometric pattern that inspires two theoretical physicists to propose a radically new type of matter, called a quasicrystal, that violates laws set in stone for centuries. Steinhardt's scientific odyssey sets out to prove that nature created quasicrystals long before humans discovered them. Along the way, his team encounters clandestine collectors, corrupt scientists, secret diaries, international smugglers and KGB agents. Their quest culminates in a daring expedition to a distant corner of the Earth, in pursuit of tiny fragments of a meteorite forged at the birth of the solar system. Steinhardt's firsthand account is an engaging scientific thriller.

BREATHE:
A Letter to My Sons
Beacon Press, September 2019

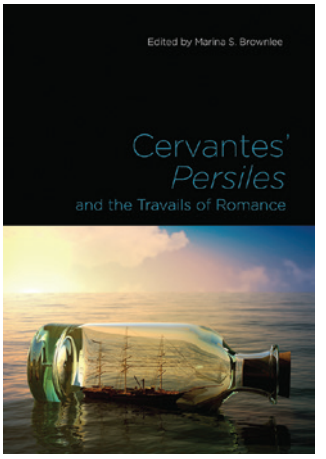
Imani Perry, the Hughes-Rogers Professor of African American Studies



Emotionally raw and deeply reflective, Perry issues an unflinching challenge to society to see black children as deserving of humanity. She admits fear and frustration for her African American sons in a society that is increasingly racist and at times seems irredeemable. However, as a mother, feminist, writer and intellectual, Perry offers an unfettered expression of love — finding beauty and possibility in life — and she exhorts her children and their peers to find the courage to chart their own paths and find steady footing and inspiration in black tradition.

Cervantes' Persiles and the Travails of Romance
University of Toronto Press, August 2019

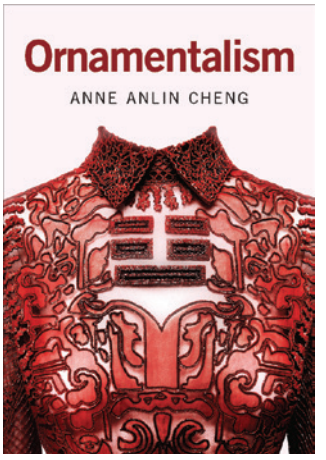
Edited by **Marina Brownlee**, the Robert Schirmer Professor of Spanish and Portuguese and Comparative Literature



This collection of original essays presents new ways of looking at Cervantes' final novel, *Persiles,* work that engages with geopolitical models of race, ethnicity, nation and religion, and takes its inspiration from the highly influential Ethiopian story (the "Aethiopika") by Heliodorus. With particular relevance to the period, Persiles questions the issue of cultural pluralism in the Spanish empire and emphasizes the need to rethink "the barbarian," which included not only the Jew, the Muslim and the Gypsy, but also the criollo, the mestizo and the indiano, a new multiracial and multiethnic reality that posed a profound challenge to early modern Spain.

Ornamentalism
Oxford University Press, January 2019

Anne Anlin Cheng, professor of English and American studies, and director of the Program in American Studies



Focusing on the cultural and philosophic conflation between the "oriental" and the "ornamental," *Ornamentalism* offers an original and sustained theory about Asiatic femininity in Western culture. This study pushes our vocabulary about the woman of color past the usual platitudes about objectification and past the critique of Orientalism in order to formulate a fresher and sharper understanding of the representation, circulation and ontology of Asiatic femininity. Tracing a direct link between the making of Asiatic femininity and a technological history of synthetic personhood in the West from the 19th to the 21st century, *Ornamentalism* demonstrates how the construction of modern personhood has been surprisingly indebted to this very marginal figure and places Asian femininity at the center of an entire epistemology of race.

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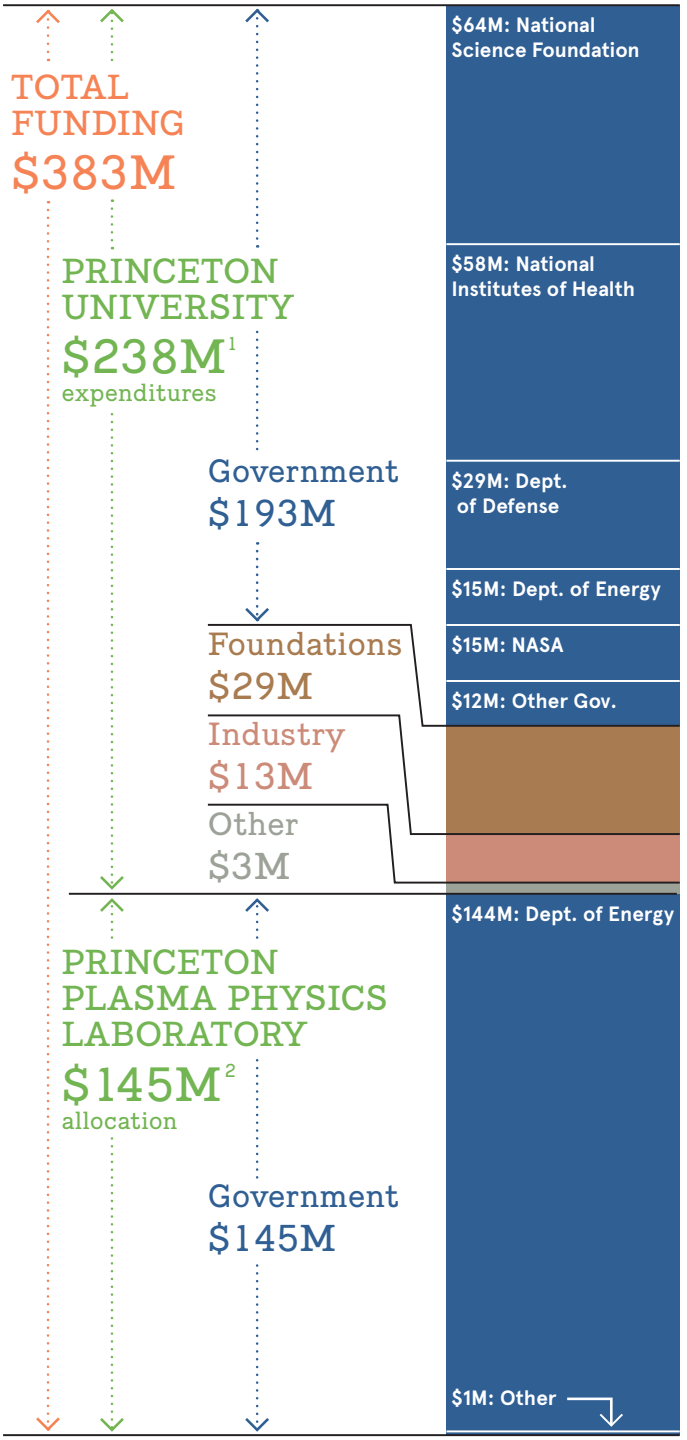
Research Report

FISCAL YEAR 2019

Major Funding Sources

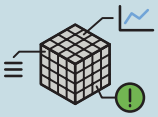


1 For fiscal year July 1–June 30.
2 For fiscal year Oct. 1–Sept. 30.

Selected Research Areas

ENERGY & ENVIRONMENT

DATA SCIENCE



HEALTH & BEHAVIOR

PUBLIC POLICY

DIGITAL HUMANITIES

FUSION POWER

PHYSICS & COSMOLOGY

THEORETICAL SCIENCE

$x^n + y^n \neq z^n$
when $n > 2$

Selected Indicators

7
STARTUPS FORMED FROM PRINCETON DISCOVERIES

48
PATENTS ISSUED

120
INDUSTRY-SUPPORTED PROJECTS

164
FINAL MASTER'S DEGREES AWARDED

398
PH.D. DEGREES AWARDED

816
PROFESSORS ENGAGED IN RESEARCH

1,577
ACTIVE SPONSORED RESEARCH PROJECTS

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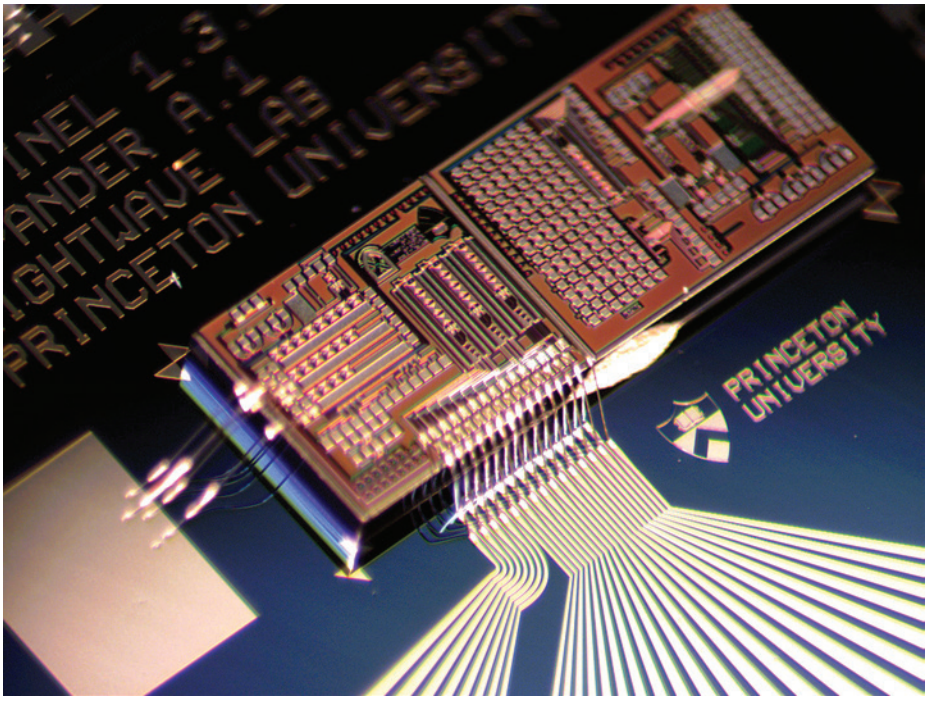

Harnessing the speed of light, a team at Princeton is building chips that use neural networks — a process inspired by the human brain — for artificial intelligence applications. These photonic chips — which use lasers, detectors and waveguides to control the flow of light — work far more quickly than traditional computer chips. "Photonics gives us the speed that we need," said Professor of Electrical Engineering Paul Prucnal.

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PHOTO BY AYMAN DAMARANY

Excavations at the Old Kingdom cemetery in Abydos, the first home of the pharaohs, provide insights into the everyday lives of ancient Egyptians. Page 4.