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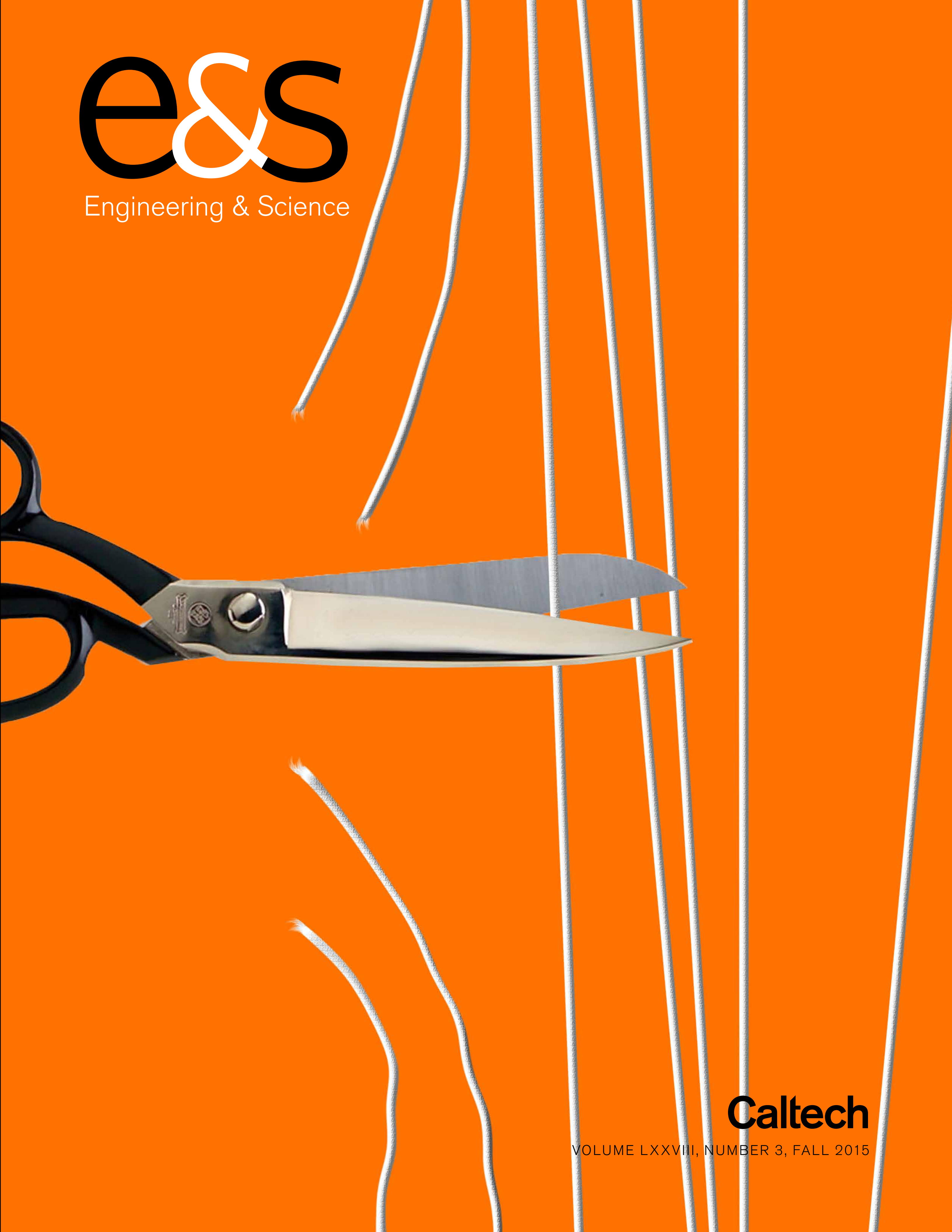

Caltech
VOLUME LXXVIII, NUMBER 3, FALL 2015

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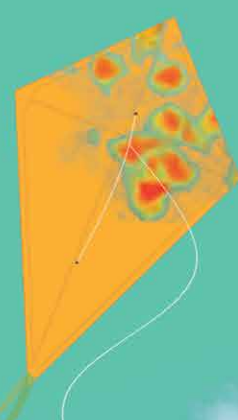


Caltech on Twitter

Follow us, retweet us, and let us know you're talking about us by including @Caltech in your tweets.

@PolycrystalhD "We save lives in the future" ~ @Caltech Grad student @bw89 speaking to her HS interns about a PhD vs. MD & the importance of basic research

@Candida_LN Walking thru Caltech with Biscuit actually makes me miss college and math & science homework. What's wrong with me?

@gravitate_to_me Today I will look at the light from dead stars, in search of a signature from inflation. My job is cool. #STEM

@kiracahill *walks into kitchen
Me "hey what are you doing?"
@CahillBrent "partial fraction decomposition"
Me *smiles like I know what that is #Caltech

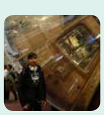
@marielas101 I had a weird dream I went to Caltech and adopted a little boy with Benedict Cumberbatch. The weirdest thing is the Caltech part.

@JadenGeller Caltech social life is homework, and Caltech parties are all-nighters.

@mananarya OMGZORBS! Something I made is on the front page of caltech.edu @ Caltech http://bit.ly/1CpSZyN

@Miquai If you hear me muttering, "Oh my," repeatedly today, I'm just practicing my @GeorgeTakei voice for the #Caltech #BoldlyGo auditions.

@gottsuiiyan OK, Caltech Science of the Solar System, I can't tell if I'm calculating surface heat on Mars or making new emoji. :-/



@iorahul Sitting right behind @astro_g_dogg, and speechless. This week at Caltech is making every single one of my childhood dreams come true.

Tweets may have been edited for spelling and grammar.

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No Strings

When Gordon (PhD '54) and Betty Moore recently pledged $100 million to Caltech, they created a permanent endowment, entrusting the choice of how to direct the funds to the Institute's leadership. "Those within the Institute have a much better view of what the highest priorities are than we could have," Gordon Moore said when the gift was announced. "We'd rather turn the job of deciding where to use resources over to Caltech than try to dictate it from outside."

Caltech provost Ed Stolper, too, is clear in his belief that this most-critical, no-strings-attached funding mechanism can make all the difference. "When someone has an idea that is good, and special," he says, "we can act quickly, even in a difficult financial time. When the money is there, people have the inspiration to think bigger."

That's why we've focused this issue of *E&S* on stories that examine what happens at Caltech when strings are cut and money is provided for instruments and centers so that researchers can pursue their most exciting—and, some might say, riskiest—ideas.

Thinking bigger—and having the unrestricted funds to make that possible—has provided instruments that gave Caltech researchers first-ever insights into the lives of viruses and bacteria (page 24). It's allowed the creation of a technique that's revealed the connections between carbon dioxide and glacial cycles and taken the temperatures of dinosaurs (page 28). It's behind the development of software that is changing how we look at financial markets (page 20).

Unrestricted funding, as impersonal as it sounds, is what gave Caltech the freedom to focus on its people, bringing together those scientists interested in "the weirdness of the world" in what has since become the Institute for Quantum Information and Matter (page 12). Such resources also created the Institute's Proteome Exploration Laboratory, through which biologists and chemists are able to explore ideas they couldn't have imagined before (page 16).

"Unrestricted funds," says Stolper, "lets us move into a field because we think it's important. It stimulates people to think of new and different things on a larger scale than they would have otherwise. It gives them a reason to dream."

—Lori Oliwenstein, Editor in Chief

Random Walk

GET A GRIP

The same forces that give gecko feet their uncanny ability to stick to just about anything may soon help scientists collect space trash. Geckos use tiny hairs that exploit attractive forces between temporary electric dipoles, called van der Waals forces, for adhesion. Now, researchers at JPL are working on gripping tools inspired by the tiny lizards that might one day be used to grab onto objects in space, like debris or defunct satellites. “The reliability of van der Waals forces, even in severe environments, makes them particularly useful for space applications,” says Aaron Parness, a JPL robotics researcher who is the principal investigator for the grippers. Recent experiments during brief periods of weightlessness on a test flight showed that the grippers could seize a 20-pound cube as it floated, as well as get a firm hold on a researcher wearing a vest made of spacecraft-material panels. The current device, made of adhesive pads, is handheld by researchers during tests, but the long-term goal is to integrate the grippers into a robotic arm.

Three Cheers for Science

Last year, Erik Sorto (above) did something he hadn't been able to do in more than a decade: he lifted a glass to his lips and took a sip. The feat represented an incredible advance not only for Sorto but also for neuroscience. Sorto is paralyzed from the neck down; with the help of a robotic arm and brain implants that assist him in turning his intentions into actual motions, he is now able to sip beverages, offer handshakes, and even play "rock, paper, scissors."

"I was surprised at how easy it was," says Sorto about the first time he was able to control a robotic limb.

Sorto's sipping success came as a participant in a clinical trial led by principal investigator Richard Andersen, Caltech's James G. Boswell Professor of Neuroscience, who has developed implantable neuroprosthetics that create natural and fluid motions by using a person's intent to move. The results of the trial were published in the May 22 edition of the journal *Science*.

"When you move your arm, you really don't think about which muscles to activate and the details of the movement. Instead, you think about the goal of the movement. For example, 'I want to pick up that cup of water,'" Andersen says. "So in this trial, we were successfully able to decode these actual intents, by asking the subject to simply imagine the movement as a whole, rather than breaking it down into myriad components."

Andersen and his colleagues were able to improve upon current neuroprosthetics by implanting them in a different brain region—the posterior parietal cortex (PPC). Most current implants target the motor cortex instead. In the clinical trial—designed to test the safety and effectiveness of this new approach—Andersen's Caltech team collaborated with surgeons at Keck Medicine of USC and the rehabilitation team at Rancho Los Amigos National Rehabilitation Center. The surgeons implanted a pair of small electrode arrays in two parts of Sorto's PPC. The arrays were connected by cable to a system of computers that processed the signals, decoded what it was Sorto intended to do, and then sent those signals to output devices that included a robotic arm developed by collaborators at Johns Hopkins University.

Once he'd recovered from the surgery, Sorto began learning how to use his thoughts and intentions to control first a computer cursor and then the robotic arm. "This study has been very meaningful to me," says Sorto. "It gives me great pleasure to be part of the solution for improving paralyzed patients' lives." —*JSC*

"You will move through life shaped by your time here, creating new spaces for yourself and for society. I wish you wholeness and magic on your journey forward."

—Caltech president Thomas Rosenbaum, addressing graduates at Caltech's 121st annual commencement ceremony on June 12, 2015.

DID YOU **KNOW?**

At press time, **47%** of students in this fall's incoming class were female, an all-time high; **49%** of acceptance letters for the class of 2019 were sent to women.

ON A ROLL People moving about Caltech's campus in giant hamster balls made of futuristic materials? It must be Ditch Day 2015. In the photo at right, Elliot Simon, then still a junior, runs in front of the Broad Center for the Biological Sciences in a Zorb ball, followed closely by alum David Ding (BS '14). The stack was themed around the 1980s video game "Where in the World is Carmen Sandiego?" The Carmen Sandiego team spent the morning collecting clues via activities that included a laser puzzle, a chemistry demonstration, and the human hamster balls. After lunch, they put the clues together and began a quest across campus to finally catch Carmen Sandiego, played by then senior Daniel Kong (BS '15), whom the team promptly tied to a tree with duct tape, as tradition dictates. They celebrated their capture (and quick release) of the elusive villain with a trip to Sky Zone, an indoor trampoline park.

Financial Fumbles

As football season starts up again this fall, it's easy to become envious of football players and their multi-million dollar contracts. But don't let the mansions and expensive cars fool you: they're just as likely to go bankrupt as the rest of us, a recent Caltech study says.

In economics, there is a well-known model called the lifecycle hypothesis that describes how people earn, spend, and save money over the course of their lifetimes. The average person's financial profile generally fits this model: when you're young, you don't earn a lot, but you need to beef up your savings for retirement; middle age is when you begin to hit your top earning potential; and when you're retired, your income is reduced, and you need to start relying on savings.

Economist Colin Camerer and former graduate student Kyle Carlson (PhD '15) wanted to see if this model held strong even in unusual cases—such as with NFL players who can earn millions of dollars right after college but then be forced into retirement by injuries in their mid-20s.

They collected NFL players' publicly available football income data and tracked actual bankruptcies of those players. What they found was that although optimal models say that NFL players should theoretically earn enough money in a few years to last them through retirement, in actuality, the players go bankrupt at the same rate as the average person who earns much less. And a player's career earnings and time in the league had no effect on this bankruptcy risk.

"We know that the hypothesis doesn't work for these people, but we can't really say why. There are a lot of ways in which the players are different from typical people," Carlson says. For example, these athletes are earning large sums of money when they are very young and might be inexperienced in financial planning. Furthermore, their risk-taking behavior on the field may also result in riskier investment decisions in life. So while your favorite player may not fumble on the field, he might drop the ball when it comes to planning for his financial future. —*JSC*

Insider Info

Biologist Grant Jensen has posted

14.5

hours of free online videos to teach others about cryo-electron microscopy. Get a closeup of that process on page 24.

There are over **100** professors, postdocs, and students in the Institute for Quantum Information and Matter. Hear what some of them have to say about the future of quantum physics on page 12.

The final draft of the speech crafted by Intel cultural anthropologist Genevieve Bell for Caltech's 121st annual commencement ceremony had

3,890

words. Read an excerpt from that address on page 33.

BIGGER DATA

Acknowledging not only the growing need among scientists and engineers for resources that can help them handle, explore, and analyze big data, but also the complementary strengths of Caltech's Center for Data-Driven Discovery (CD³) and JPL's Center for Data Science and Technology (CDST), the two centers have formally joined forces, creating the Joint Initiative on Data Science and Technology.

Individually, each center strives to provide the intellectual infrastructure, including expertise and advanced computational tools, to help researchers and companies from around the world analyze and interpret the massive amounts of information they now collect using computer technologies, in order to make data-driven discoveries more efficient and timely.

"We've found a lot of synergy across disciplines and an opportunity to apply emerging capabilities in data science to more effectively capture, process, manage, integrate, and analyze data," says Daniel Crichton, manager of the CDST. "JPL's work in building observational systems can be applied to several disciplines from planetary science and Earth science to biological research."

The Caltech center is also interested in this kind of methodology transfer—the application of data tools and techniques developed for one field to another. The CD³ recently collaborated on one such project with Ralph Adolphs, Bren Professor of Psychology and Neuroscience and professor of biology at Caltech. They used tools based on machine learning that were originally developed to analyze data from astronomical sky surveys to process neurobiological data from a study of autism.

"We're getting some promising results," says George Djorgovski, professor of astronomy and director of CD³. "We think this kind of work will help researchers not only publish important papers but also create tools to be used across disciplines."

Both the CD³ and the CDST began operations last year. The Joint Initiative already has a few projects under way in the areas of Earth science, cancer research, health care informatics, and data visualization.

"The hope is that we can accumulate experience and solutions and that we will see more and more ways in which we can reuse them to help people make new discoveries," says Djorgovski. "We really do feel like we're one big family, and we are trying to help each other however we can." —*KF*

An Advanced Look

Caltech president Thomas Rosenbaum (second from right) inspects a vacuum chamber at the Laser Interferometer Gravitational-Wave Observatory (LIGO) in Hanford, Washington, during a tour lead by observatory head Frederick Raab (right) at the May 19 Advanced LIGO dedication. Inside the chamber, in an ultrahigh-vacuum environment, several pristine mirrors hang in carefully balanced suspension, directing laser light into the gravitational-wave detector's 4-kilometer beam paths. LIGO was designed and is operated by Caltech and MIT, with funding from the National Science Foundation (NSF). Advanced LIGO, also funded by the NSF, is expected to begin its first searches for gravitational waves this fall, possibly as you are reading these pages.

The Advanced LIGO Project is a major upgrade that should increase the sensitivity of the detector by a factor of 10 and provide a 1,000-fold increase in the number of astrophysical candidates for gravitational-wave signals. "Advanced LIGO represents a critically important step forward in our continuing effort to understand the extraordinary mysteries of our universe," said NSF director France Córdova (PhD '79) at the dedication. "It gives scientists a highly sophisticated instrument for detecting gravitational waves, which we believe carry with them information about their dynamic origins and about the nature of gravity that cannot be obtained by conventional astronomical tools."

On the Grounds

The bas relief of "nature's engineer" seen here was made by Albert Stewart, a world-renowned sculptor known for his animal subjects, and has been hanging around on campus since 1962. More recently, the surly-looking rodent became one of the first images to appear on Caltech's new Instagram account (@caltechedu). Where, besides online, can you find this lifelike representation of Caltech's beloved mascot?

Answer: This beaver guards the bookstore, hanging above its main doorway.

BY THE NUMBERS: WATER CONSERVATION

Recognizing the importance of reducing water use in the face of California's extreme drought, Caltech began addressing the issue well before government regulations were tightened; some of those efforts are described below. For more on how the Institute is working to address the complex challenges around the drought, visit ***sustainability.caltech.edu***.

Caltech has reduced total water consumption by approximately **38** percent in the last eight years.

Only **16** percent of campus water is used for outdoor irrigation.

The nine LEED buildings on campus are **30** percent more water efficient than code requires.

74 percent of grass-cover on campus is low-water-use turf.

Caltech currently has **11** water conservation projects in the works.

FACULTY FOOTNOTES

Each year since 1993, the Richard P. Feynman Prize for Excellence in Teaching has been given to a Caltech professor "who demonstrates, in the broadest sense, unusual ability, creativity, and innovation" in teaching. This year's prize was awarded to Professor of English Kevin Gilmartin, who has taught at Caltech for the past 24 years.

Gilmartin was nominated by students in several different disciplines, who praised his enthusiasm and accessibility, his artful handling of classroom discussion and debate, and his patient tutoring in the fine art of writing.

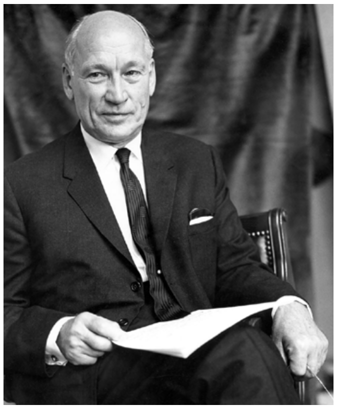
The Feynman Prize committee described Gilmartin as "an example to the Institute of the possibilities for engagement, discovery, and growth through classroom teaching."

Here are just a few things that the anonymous nominators had to say about Gilmartin:

- "Between students and professors there lies an impersonal wall, but Professor Gilmartin bulldozes it down. If I pop into his office without any warning, he'll talk to me for an hour on anything there is to talk about, from the bike traffic in Pasadena, to how much Jane Austen rocks, to how Aeneas is a jerk."

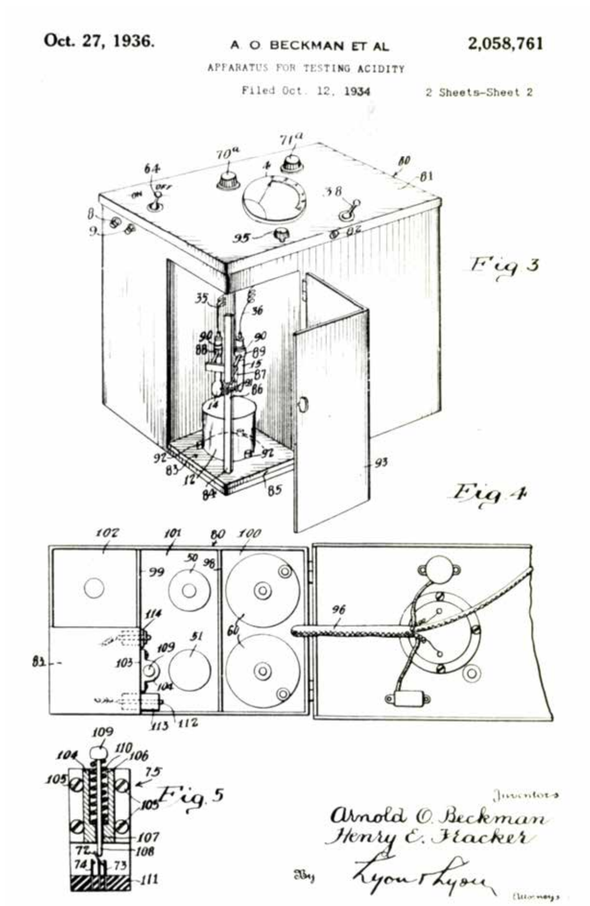
- "Not only did Professor Gilmartin try to involve all of his students in class discussions, but also he gave us unique opportunities to further our studies. Most memorably, he invited me and my classmates to have dinner with Sinead Morrissey, a contemporary poet whose work we were studying. By the end of that term, I was no longer plagued with self-doubt and decided to pursue a minor in English."

- "Professor Gilmartin is someone with whom I'd spend a day in a hole-in-the-wall coffee shop, sampling exotic teas and coffee and reading poetry. He's my John Keating (from the Dead Poets Society). He's the one who not only savors how language feels on tongues and develops heart-tugging or heart-emptying stories, but he is also generous to invite us all into that experience."



MAKING LEMONADE FROM LEMONS:
The Birth of the pH Meter

Arnold O. Beckman was a Caltech alumnus (PhD '28), former faculty member, and trustee. He was also the founder of Beckman Instruments (now Beckman Coulter), a company that began with Beckman's invention of the pH meter, now one of the most widely used pieces of laboratory equipment in the world. The pH meter's story started in 1934, when one of Beckman's undergrad classmates from the University of Illinois at Urbana —Glen Joseph, who was then working for the California Fruit Growers Exchange—came to Beckman's Caltech office with a lemon problem. Here is how Beckman recalled that encounter during a 1978 interview with Mary Terrall for the Caltech Oral Histories Project.



[Joseph] had to measure the acidity of lemon juice that had been treated with sulfur dioxide. He was making by-products from lemon juice—pectin, citric acid, things like that. . . . He had to use a glass electrode. And at that time the only glass electrode available was one made by Leeds & Northrup, and that used a high-sensitivity galvanometer.

Well, because of the poor electrical sensitivity of the galvanometer, the glass electrode had to be made so large in diameter that it was very fragile. The glass electrodes were always breaking, and if it wasn't that, the galvanometer itself would break. So . . . I built him an instrument in late '34, maybe early '35. He came back in two or three months and wanted to know if I could build him another one—others in the laboratory were using the first one and he wanted to have one for his own use. So I did build him another. Then I thought, "Gee, if he could use two of these in that little laboratory he has, maybe there's a market for them."

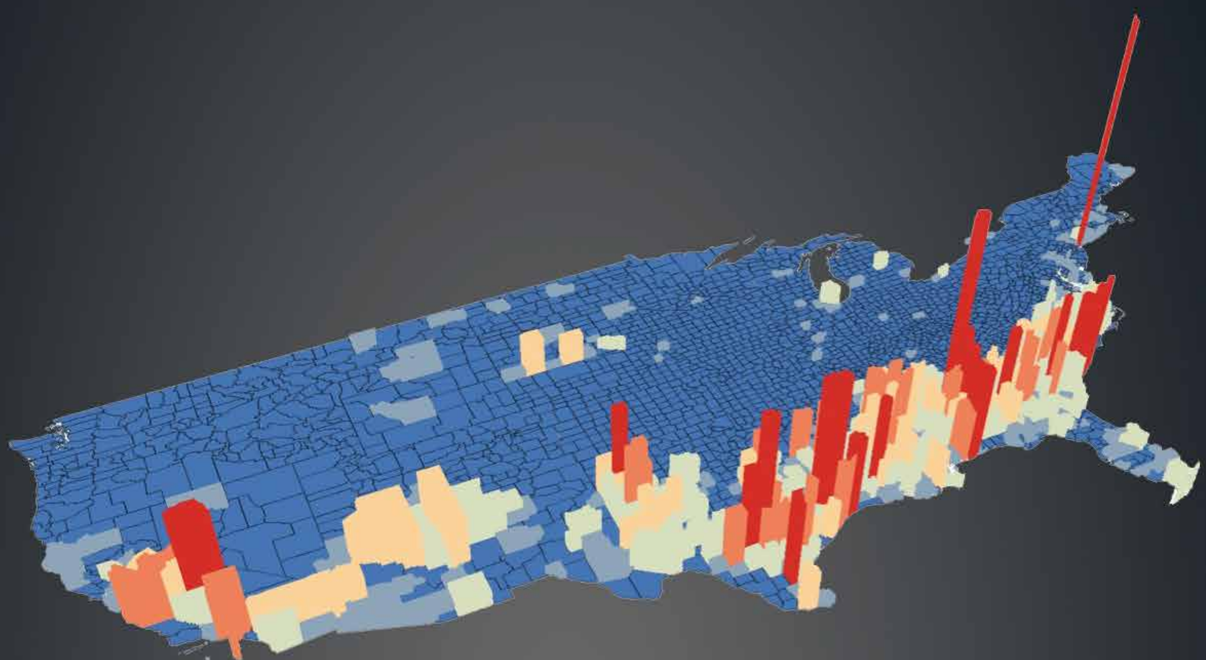
I was doing this work out at 3600 East Colorado Street, where Fred Henson had an instrument shop. Fred Henson used to be the instrument maker for the chemistry department. . . . He allowed me to set up space in the back of the sheet-metal shed he had, where he stored his lumber and his Studebaker truck. We partitioned off nine feet across the back of the shed, and that was where we started.

None of the work was done on the campus. The reason for that was that at that time there was a very strong feeling that commercialism should never enter into the thinking of anybody on the staff.

That, of course, all changed with World War II. . . .

By 1939, the company had grown to the size that somebody had to run it full-time. I was running it just part-time, evenings and weekends. So I had to make a decision—and this was a major decision—whether to leave Caltech, give up the academic field, and go into business, or to stay there and get somebody else to run the business. Well, by this time, I was having much fun with the business, and furthermore I found that I would be keeping in touch with science, because the instruments were, of course, being used in scientific laboratories. I was exposed to all sorts of new applications in science, so I felt I would not be divorcing myself from science entirely. So I made the decision to leave and go into business.

This abridged excerpt appears courtesy of the Caltech Archives. Find the full transcript online at oralhistories.library.caltech.edu/78.



available now on **CALTECH.EDU**

ROCK THE VOTE

Constitutional law scholar and Caltech professor of history and social science Morgan Kousser discusses racial discrimination in U.S. elections and the 2013 Supreme Court decision that overturned the Voting Rights Act. Read the interview at **bit.ly/1TORvCR**.

Watch

Caltech biologists have discovered a previously unknown self-repair mechanism—the reorganization of existing anatomy to regain symmetry—in a species of jellyfish. Learn more at **youtube.com/caltech.**

Read

Caltech researchers are making headlines with their work and lending expertise to news articles published across the globe. To keep up with these stories, visit "Caltech in the Media" at **caltech.edu/news/in-the-media**.

Engage

The 2015–16 Watson Lecture Series kicks off on Wednesday, October 14, 2015, at 8 p.m. with JPL's Paul Weissman, an expert on planetary ice. Find out more at **caltech.edu/calendar/public-events**.

FULL CIRCLE PHYSICS

From left: IQIM members John Preskill, Shaun Maguire, Chandni U., and Oskar Painter.

Caltech's Institute for Quantum Information and Matter (IQIM) began in 2010 as the Center for Exotic Quantum Systems, funded by the Gordon and Betty Moore Foundation as part of what it called its Caltech Commitment. By 2011, it had become so successful that it did exactly what the Moore Foundation had hoped it would do—it outgrew its original concept, garnering wide interest and additional funding from the National Science Foundation to become a Physics Frontiers Center that studies "physical systems in which the weirdness of the quantum world becomes manifest on macroscopic scales." Its research programs range from quantum information science to quantum condensed-matter physics, quantum optics, and the quantum mechanics of mechanical systems. By bringing together theorists and experimentalists under the same roof, IQIM has created a continuous, collaborative feedback loop to take quantum science to the next level.

With the help of interviews conducted by IQIM communications coordinator Crystal Dilworth (PhD '14) and filmmaker Iram Parveen Bilal (BS '04), E&S *talked with several IQIM scientists about the frontiers of quantum science, the role IQIM plays in exploring that frontier, and the question oft thought but rarely spoken: Why should we care? Here—in a "conversation" assembled from separate interviews—are some of their insights into what makes the world of the tiny such a big deal.*

WHY IS QUANTUM SCIENCE SO EXCITING?

John Preskill, the Richard P. Feynman Professor of Theoretical Physics: Everybody wants to understand the world, right? And there are all kinds of things that I don't understand. But physics is a way of making sense of the world. And it works. It's an amazing thing. It keeps happening again and again—that we can formulate these simple laws; we can do calculations on a pad of paper with a pen, which describe very deep and subtle things about nature; and we can test those ideas; and they *work*. It's so astonishing.

This is an amazing time in quantum science. A new frontier of physics is opening up, which is very fundamental and exciting. You can call it the entanglement frontier, or the complexity frontier. New phenomena occur when you put many particles together, behavior we can't simulate using our ordinary digital computers. In some cases we can predict accurately what will happen, but in many cases we don't know what to expect. Eventually this new frontier will have a big impact on technology—I don't think there's any doubt about that. But that's not really what excites us now. What excites us are the opportunities for fundamental discovery.

Imagine that for thousands of years we've been trying to push science and technology forward, but we didn't know anything about decimal arithmetic; we were stuck using Roman numerals. There are so many things we would like to be able to do, problems to solve, mathematical challenges, but we just don't have the right tools, the right computational concepts to go forward.

Quantum computing is like that. All these thousands of years human civilization has been missing this special sauce that is going to take information to a new level. And now we can glimpse what it is. We don't yet know for sure where it's leading. But it's going to be something big.

Chandni U., IQIM postdoctoral scholar in physics: Quantum science is fun and tough because it is often hard to explain or comprehend. It breaks our conventional understanding of the way the world works. I study the tunneling of electrons in atomically thin systems, and when I need to explain it to friends or family, I still use analogies like a lion penetrating through an infinitely tall wall, which is a bizarre concept in the world we are used to.

WE'RE AN ENTANGLED COMMUNITY OF SCIENTISTS WITH DIFFERENT BACKGROUNDS, BUT WITH ENOUGH COMMON GROUND TO ENGAGE WITH ONE ANOTHER FRUITFULLY.

This journey toward understanding something that we see around us is very stimulating. Even if it is something that the whole world already knows, when you learn it in a textbook, solve an equation, or measure something in the lab, that feeling is very exciting and encouraging. You don't do science hoping to make discoveries on a daily basis. The quest and little findings push you every single day. But on rare days you do observe some new phenomenon, something that only you have noticed. Even if it is a small discovery, it is thrilling because you know you have just nudged the boundaries of knowledge a bit.

Shaun Maguire, graduate student in mathematics: We've kind of made it past an inflection point in terms of actually being able to do experiments that probe the foundations of quantum mechanics. The sheer diversity of experiments happening right now is giving theorists a lot of ideas about what research directions to pursue next.

Oskar Painter, the John G Braun Professor of Applied Physics: To me, quantum physics is one of the more interesting areas of science in that we have solid mathematical models for predicting quantum behavior, but we are still rather immature in our ability to utilize these models in practice, either in calculating the properties of complex quantum systems or in building technologies that take advantage of uniquely quantum features. As a result, we don't fully appreciate yet all the subtle aspects of quantum systems, and there are a wide range of interesting fundamental and applied problems to be studied in quantum physics. Being an engineer at heart, I am drawn to the opportunities to develop new, more powerful technologies utilizing the quantum features of nature.

WHAT IS IQIM ALL ABOUT, AND WHY IS IT SPECIAL?

Preskill: IQIM is, first of all, an assemblage of different research groups—it involves 20 Caltech faculty members all doing fantastic science. IQIM brings us together, sparking progress that just wouldn't happen if these groups were acting individually rather than as part of a larger community. If you bring theorists in close contact with experimentalists and you start talking about the problems of common interest and really seriously engage with one another, it gives you new ideas. You think about things in a different way. You develop an understanding of what the theorists can and can't do, and what the experimentalists can and can't do. That's really why it's important that we are a unified institute rather than just a bunch of groups.

Painter: Experimentally, within IQIM, we are exploring a diverse set of research topics. These include fundamental studies of materials with topological order arising from long-range quantum entanglement between particles, as well as of new synthetic quantum materials that can be built up from individual gas-phase atoms interacting with photons in nano-structured materials. Researchers are also developing new techniques and technologies for performing precision measurement of mechanical objects that meet or exceed standard quantum limits set by the intrinsic uncertainty or "fuzziness" of quantum-mechanical systems. Such methods, for instance, are crucial to instruments such as the Laser Interferometer Gravitational-Wave Observatory that are searching for the hints of gravitational waves in the tiny deflections of mechanically compliant mirrors.

The IQIM is special in that we experimentalists maintain close contact with our theoretical colleagues, learning about ideas that may be 10, 20, or even 50 years ahead of their time. This gives us a great advantage in picking interesting problems to work on. For instance, a new research effort in my own group seeks to exploit the properties of superconducting electrical circuits to build quantum circuits of artificial "atoms" that can perform quantum computations, a computing method thought to be much more powerful than can be realized with classical machines. The hardware we are developing has been around for a little over a decade, but new, important ideas for how to effectively use the hardware are being developed today by IQIM theorists such as John Preskill, Alexei Kitaev, and their students and postdocs.

Maguire: The IQIM is this ecosystem of people thinking about problems that exist on a one-year timescale all the way to the 100-year-and-more timescale. I am all the way on the furthest extreme. But you have people who are thinking about the next generation of how you can transmit quantum information about the world—you can think of this as the next version of the Internet, the quantum Internet. We have people making breakthroughs in materials science and on the verge of fundamental physics, things like exploring topological insulators, people working on graphene, which has a lot of promising applications in a huge number of fields.

We're about four years into IQIM, and it just feels like there are enough ideas floating around and enough people doing really interesting things that some of those things are going to stick and become huge, substantial breakthroughs. It's an exciting thing to be a part of right now.

Chandni: IQIM is a conglomeration of people with varied interests who are extremely passionate about their science. We think of different aspects of quantum science, computing, and matter in our confined spaces, but when together as an entity we focus on the bigger picture of creating and manipulating the next generation of quantum computers and related applications. Personally, IQIM has taught me to think big. We often narrow down our thoughts and scientific perspectives because we are so focused on tackling the day-to-day issues with our research. However, IQIM brings together those many aspects under a broad vision and gives them depth and purpose.

Preskill: Big scientific advances often occur when different ideas collide and get synthesized. We're seeing that in a number of different ways in what we're doing at IQIM today.

Quantum entanglement is a unifying idea that encompasses a lot of the science that we work on. When a quantum system is highly entangled, that means the information carried by the system is spread out very nonlocally. You can't read that information by looking at the parts of the system one at a time, because the information is really stored in how the parts are correlated with one another. By thinking hard about entanglement, applying ideas that were originally developed for understanding quantum computers, we've found new ways to classify the different possible types of quantum materials. Insights borrowed from quantum computing are even giving us new ways to approach deep issues in quantum gravity, like the quantum properties of black holes and the fundamental structure of space and time. What's really exciting to me is that we might be able to test some of these ideas experimentally.

It takes a community to make progress because these problems are hard, they're very interdisciplinary. Computer scientists have part of the answer, experimental physicists know a lot of the tools that are relevant, theoretical physicists, people from information theory—all of them have pieces of the puzzle. And you have to get them together and create an intellectual climate where ideas are flying around and everyone benefits from everyone else's knowledge and background—that's what we're doing at IQIM. We're an entangled community of scientists with different backgrounds, but with enough common ground to engage with one another fruitfully. It's really exciting.

Public outreach is also a huge part of what we do at IQIM. We produce videos with Jorge Cham, the creator of PhD Comics, which explain quantum concepts in an engaging way. In collaboration with Google and MinecraftEdu we created qCraft, a game that teaches kids about how to manipulate quantum systems. Our blog Quantum Frontiers provides a personal perspective on quantum science. See our website for much more.

IT'S EXCITING TO YOU, BUT WHY SHOULD THE REST OF US CARE ABOUT QUANTUM SCIENCE?

Painter: When we start talking about quantum mechanics nowadays to a layperson, I think it's a lot easier because the experiments we're doing are more tangible. We've built up these quantum systems to a larger scale, to scales in which we start to have an everyday appreciation for the objects involved. It's not just at the atomic scale. For example, we are now able to measure the quantum properties of mechanical objects, ones which can be seen with the naked eye, or of electrical circuits similar to those found in your cell phone. So it's become a little bit easier to talk about quantum mechanics to the average person on the street.

It's also very likely that quantum mechanical concepts will be more relevant to such a person. In the decades to come, as we become more proficient in making devices that compute things or communicate information utilizing the principles of quantum mechanics, there will be a need to understand concepts such as superposition and entanglement by those who use these technologies.

Chandni: At least in some form, you will probably have a quantum computer in a few years' time. As for materials, topological insulators, which is one of the things we talk about, I think it will have a lot of other applications like in power devices, where the goal is to have low power consumption. Graphene people say *that* material can revolutionize a lot of fields, including flexible electronics and so on.

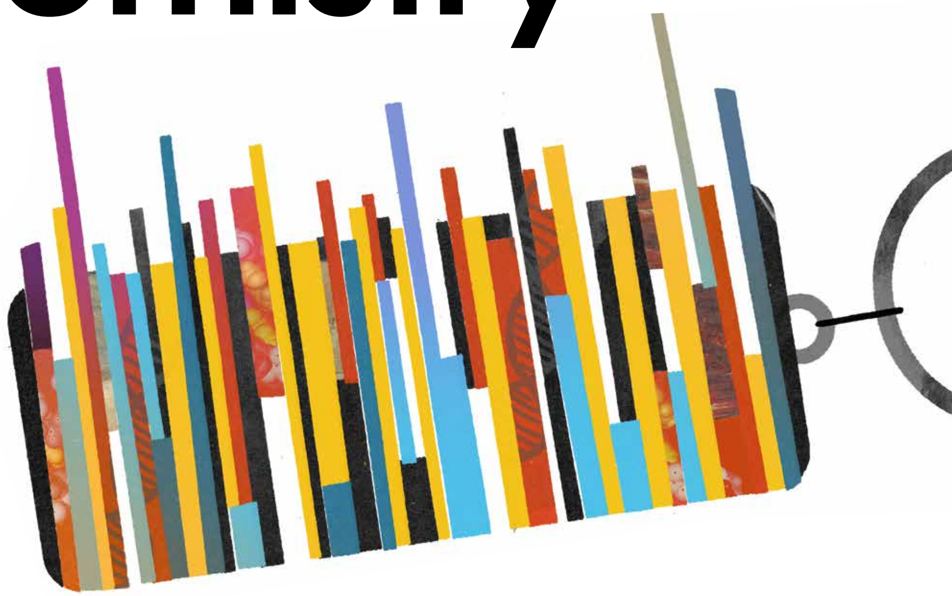
We need to remember that the public was not that interested in normal computers not that long ago. Right now, quantum science is just cool science stuff. But if you want to have a good future where you have even smarter smartphones, then quantum computing is important.

Preskill: How is this going to affect people in their everyday lives? I don't know. But I think it will, and in profound ways. And the reason I think that . . . well, of course we know how important information and information processing are now in our daily lives. And what we're talking about with quantum computing is a whole different way of thinking about and manipulating information. It's not just a much, much faster computer; it's really a different paradigm for what information is and how we can make use of it.

It's kind of a mystery why physics is so successful, why we, human beings who have many limitations, who evolved for a much different purpose than to probe the deepest secrets of nature, can be so successful at it. It's hard. There are many puzzles. Nature is subtle and it's always a struggle to answer the big questions, but we make progress and it's just so satisfying when we do. e&s

Unlocking the Chemistry of Life

by Jessica Stoller-Conrad



In just the span of an average lifetime, science has made leaps and bounds in our understanding of the human genome and its role in heredity and health—from the first insights about DNA structure in the 1950s to the rapid, inexpensive sequencing technologies of today. The 20,000 genes of the human genome—each made of a sequence of DNA bases—encode proteins to carry out the countless functions that are key to our existence. But we know much less about how this collection of proteins supports the essential functions of life than we do about the genes that built them.

In order to understand the role each of these proteins plays in human health—and what goes wrong within them to cause disease—biologists need to figure out what these proteins are and how they function. Several decades ago, biologists realized that to answer these questions on the scale of the thousands of proteins in the human body, they would have to leave the comfort of their own discipline to get some help from a standard analytical-chemistry technique: mass spectrometry. Since 2006, Caltech's Proteome Exploration Laboratory (PEL) has been building on this approach to bridge the gap between biology and chemistry, in the process unlocking important insights about how the human body works.

Scientists can easily sequence an entire genome in just a day or two, but sequencing a proteome—all of the proteins encoded by a genome—is a much greater challenge, says Ray Deshaies, protein biologist and founder of the PEL. "One challenge is the amount of protein. If you want to sequence a person's DNA from a few of their cheek cells, you first amplify—or make copies of—the DNA so that you'll have a lot of it to analyze. However, there is no such thing as protein amplification," Deshaies says. "The number of protein molecules in the cells that you have is the number that you have, so you must use a very sensitive technique to identify those very few molecules."

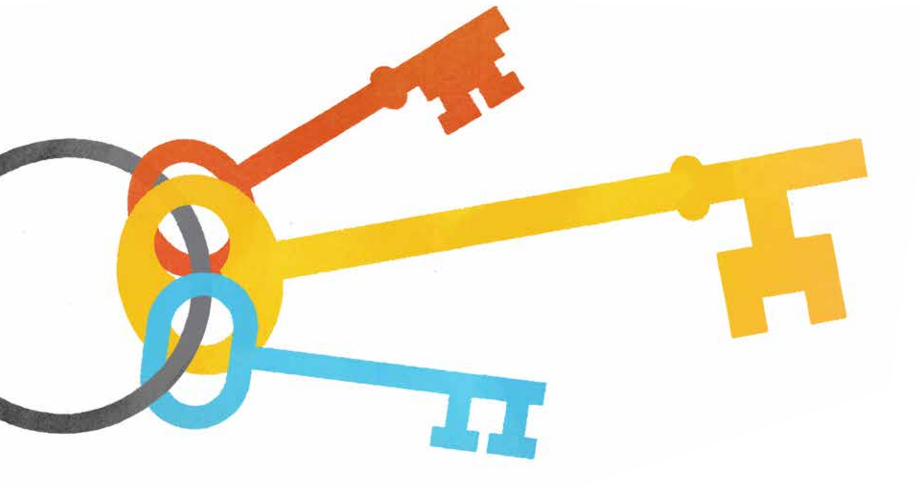
The best means available for doing this today is called shotgun mass spectrometry, Deshaies says. In general, mass spectrometry allows researchers to identify the amount and types of molecules that are present in a biological sample by separating and analyzing the molecules as gas ions, based on mass and charge; shotgun mass spectrometry—a combination of several techniques—applies this separation process specifically to digested, broken-down proteins, allowing researchers to identify the types and amounts of proteins that are present in a heterogeneous mixture.

The first step of shotgun mass spectroscopy entails digesting a mixture of proteins into smaller fragments called peptides. The peptides are separated based on their physical properties, and then they are sprayed into a mass spectrometer and blasted apart via collisions with gas molecules such as helium or nitrogen—a process that creates a unique fragmentation pattern for each peptide. This pattern, or "fingerprint," of each peptide's fragmentation can then be searched on a database and used to identify the protein the peptide came from.

"Up until this technique was invented, people had to take a mixture of proteins, run a current through a polyacrylamide gel to separate the proteins by size, stain the proteins, and then physically cut the stained bands out of the gel to have each individual protein species sequenced," says Deshaies. "But mass spectrometry technology has gotten so good that we can now cast a broader net by sequencing everything, then use data analysis to figure out what specific information is of interest after the dust settles down."

Deshaies began using this shotgun mass spectrometry in the late 1990s, but because the technology was still very new, all of the protein analysis had to be done at the outside laboratories that were inventing the methodology. In 2001, after realizing the potential of this field-changing technology, he and colleague Barbara Wold, the Bren Professor of Molecular Biology, applied for and received a Department of Energy grant for their very own mass spectrometer. When the instrument arrived on campus, demand began to surge.

"Barbara and I were first just doing experiments for our own labs, but then other people on campus wanted us to help them apply this technology to their research problems," Deshaies says.



So he and Wold campaigned for a larger, ongoing center where anyone could begin using mass spectrometry resources for protein research. In 2006, Deshaies and then chair of the Division of Biology (now the Division of Biology and Biological Engineering) Elliot Meyerowitz petitioned the Gordon and Betty Moore Foundation to secure funding for a formal Proteome Exploration Laboratory, as part of the foundation's commitment to Caltech.

The influx of cash dramatically expanded the capabilities and resources that were available to the PEL, allowing it to purchase the best and fastest mass spectrometry instruments available. But just as importantly, it also meant that the PEL could expand its human resources, Deshaies adds. It was mostly students who were running the instruments in the Deshaies lab, he says, so when they graduated or moved on, gaps were left in expertise. Sonja Hess came to Caltech in 2007 to fill that gap as director of the PEL.

Hess, who came from a proteomics lab at the National Institutes of Health, knew the challenges of running an interdisciplinary center such as the PEL. Although the field of proteomics holds great promise for understanding big questions in many fields, including biology and medicine, mass spectrometry is still a highly technical method involving analytical chemistry and data science—and it's a technique that many biologists were never trained in. Conversely, many chemists and mass spectrometry technicians don't necessarily understand how to apply the technique to biological processes.

By encouraging dialogue between these two groups, Hess says, the PEL crosses that barrier, helping apply mass spectrometry techniques to diverse research questions from more than 20 laboratories on campus.

Creating this interdisciplinary and resource-rich environment has enabled a wide breadth of discoveries, says Hess. One major user of the PEL, chemist David Tirrell, has turned to the center for many collaborations involving a technique he developed with former colleagues Erin Schuman and Daniela Dieterich called BONCAT (for "bioorthogonal noncanonical amino-acid tagging").

BONCAT uses synthetic molecules that are not normally found in proteins in nature, and that carry particular chemical tags. When these artificial amino acids are incubated with certain cells, they are taken up by the cells and incorporated into all newly formed proteins in those cells. The tags then allow researchers to identify and pull out proteins from the cells, thus enabling them to wash away all of the other untagged proteins from other cells that aren't of interest. When this method is combined with mass spectrometry techniques, it enables researchers to achieve specificity in their results and determine which proteins are produced in a particular subset of cells during a particular time.

"In my own laboratory, we work at making sure the method is adapted appropriately to the specifics of a biological problem. But we rely on collaborations with other laboratories to help us understand what the demands on the method are and what kinds of questions would be interesting to people in those fields," Tirrell says.

For example, Tirrell collaborated with biologist Paul Sternberg and the PEL, using BONCAT and mass spectrometry to analyze specific proteins in a few cells from a whole organism, a feat that had never been accomplished before. Using the nematode *C. elegans*, Sternberg and his team applied the BONCAT technique to tag proteins in the 20 cells of the worm's pharynx and then used the PEL resources to analyze proteome-wide information from just those 20 cells. The results, including identification of proteins that were not previously associated with the pharynx, were published in the *Proceedings of the National Academy of Sciences* in 2014.

The team is now trying to use the same technique on a single pair of neurons that help the worm to sense and avoid harmful chemicals—a first step in learning which proteins are essential to producing this responsive behavior. But analyzing protein information from just two cells is a difficult experiment, says Tirrell.

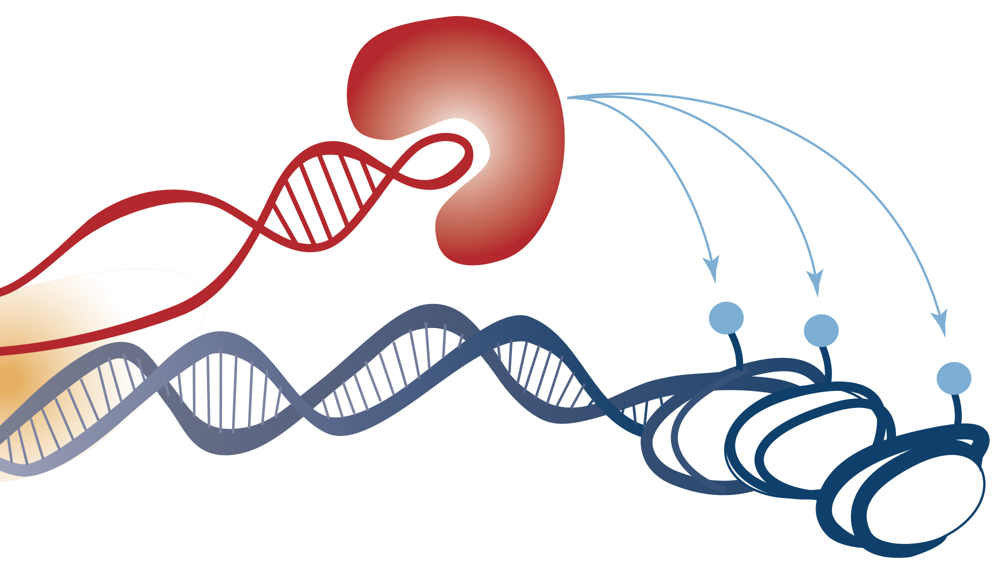
"The challenge comes in separating out the proteins that are made in those two cells from the proteins in the rest of the hundreds of cells in the worm's body. You're only interested in two cells, but to get the proteins from those two cells, you're essentially trying to wash away everything else—about 500 times as much 'junk' protein as the protein that you're really interested in," he says. "We're working on these separation methods now because the ultimate experiment would be to find a way to use BONCAT and mass spec to pull out proteomic information from a single cell in an animal."

Although Deshaies says that the PEL resources have become invaluable to his work, he adds that what makes the laboratory unique is how it benefits the entire Institute—a factor that he hopes will encourage further support for its mission.

This next step is an important one, but Tirrell says that an advantage of the PEL is that the laboratory's staff can focus on optimizing the very technical mass spectrometry aspects of an experiment, while researchers using the PEL can focus more holistically on the question they're trying to answer. This was also true for biologist Mitch Guttman, who asked the laboratory to help him develop a mass spectrometry–based technique for identifying the proteins that hitchhike on a class of RNA genes called lncRNAs.

Long noncoding RNAs—or lncRNAs (pronounced "link RNAs") for short—are abundant in the human genome, but scientists know very little about how they work or what they do. Although it's known that protein-coding genes start out as DNA, which is transcribed into RNA, which is then translated into the gene product, a protein, lncRNAs are never translated into proteins. Instead, they're thought to act as scaffolds, corralling important proteins and bringing them to where they're needed in the cell. In a study published in April 2015 in *Nature*, Guttman used a specific example of a lncRNA, a gene called Xist, to learn more about these hitchhiking proteins.

"The big challenge to doing this was technical; we've never had a way to identify which proteins are actually interacting with a lncRNA molecule. By working with the PEL, we were able to develop a method based on mass spectrometry to actually purify and identify this complex of proteins interacting with a lncRNA in living cells," Guttman says. "Once we had that information, we could really start to ask ourselves questions about these



The lncRNAs that Mitch Guttman studies don't encode proteins, rather they act as scaffolds, shuttling proteins to their destination within the cell. Above is a schematic of a lncRNA (red helical structure) in action, escorting a protein (red "C" shape) to DNA targets (light blue) within the cell.

proteins and how are they working."

Using this new method, called RNA antisense purification with mass spectrometry (RAP-MS), Guttman's lab determined that 10 proteins associate with the lncRNA Xist, and that three of those 10 are essential to the gene's function—inactivating the second X chromosome in women, a necessary process that, if interrupted, results in the death of female embryos early in development.

Guttman's findings marked the first time that anyone had uncovered the detailed mechanism of action for a lncRNA gene. For decades, other research groups had been trying to solve this problem; however, the collaborative development of RAP-MS in the PEL provided the missing piece.

Even Deshaies, who began doing shotgun mass spectrometry experiments in his own laboratory, now exclusively uses the PEL's resources and says that the laboratory has played an essential support role in his work.

He studies the normal balance of proteins in a cell and how this balance changes during disease. In a 2013 study published in *Cell*, his laboratory focused on a dynamic network of protein complexes called SCF complexes, which go through cycles of assembly and dissociation in a cell depending on when they are needed.

Because there was no insight into how these complexes form and disassemble, Deshaies and his colleagues used the PEL to quantitatively monitor how this protein network's dynamics were changing within cells. They determined that SCF complexes are normally very stable, but in the presence of a protein called Cand1 they become very dynamic and rapidly exchange subunits. Since some components of the SCF complex have been implicated in the development of human diseases such as cancers, work is now being done to see if Cand1 holds promise as a target for a cancer therapeutic.

Although Deshaies says that the PEL resources have become invaluable to his work, he adds that what makes the laboratory unique is how it benefits the entire Institute—a factor that he hopes will encourage further support for its mission.

"The value of the PEL is not just about what it contributes to my lab or to Dave Tirrell's lab or to anyone else's," he says. "It's about the breadth of PEL's impact—the 20 or so labs that are bringing in samples and using this operation every year to do important work, like solving the mechanism of X-chromosome inactivation in females." e&s

Raymond Deshaies is a professor of biology, an investigator with the Howard Hughes Medical Institute (HHMI), and the executive officer for molecular biology at Caltech. His work is funded by HHMI and the National Institutes of Health (NIH).

Sonja Hess is the director of the Proteome Exploration Laboratory at Caltech. Three of the PEL's instruments are funded by NIH, the Gordon and Betty Moore Foundation, HHMI, and the Beckman Institute. The laboratory is led by executive director Shu-ou Shan, professor of chemistry.

David Tirrell is Ross McCollum–William H. Corcoran Professor and professor of chemistry and chemical engineering and director of the Beckman Institute at Caltech. His collaboration with Paul Sternberg, the Thomas Hunt Morgan Professor of Biology and an investigator with HHMI, was supported by HHMI.

Mitchell Guttman is an assistant professor of biology at Caltech. His research with Xist was made possible by NIH.

The Science of Economics

by Kimm Fesenmaier

John Ledyard is an economist, but when he talks about the work that he and his colleagues who study socioeconomic systems at Caltech have completed over the last decade with the support of the Gordon and Betty Moore Foundation, he looks to astronomy for an appropriate metaphor. He's trying to find a way to explain the importance and utility of a suite of software they have developed.

"It's kind of like building a new, powerful telescope," Ledyard says. "It's not that all of the astronomers using that telescope are working on the same thing, but because of the larger telescope, they can all do a lot more, different work. What the Moore Foundation grant enabled us to do was to build a bigger measurement device."

The new software, along with funding, has enabled researchers to create and run experiments in the lab to test all sorts of market systems involving social interactions—everything from the effect of inequality on tax rates to the best way for the United Nations to auction off pallets of natural rubber in Vietnam.

"We bring big problems down to something you can actually study," says Charlie Plott, a pioneer in the field of experimental economics—the practice of testing economic theories by studying the way that people *actually* behave in situations that involve, for example, markets, voting, or group decision making, by creating those scenarios under controlled lab conditions using real-life incentives, such as money. "Creating experiments forces you to get into the detail; observing those experiments gets you even more into the detail. And the devil in these sorts of problems is always in the detail."

That has proven to be the case, for example, in the work Plott has done designing and improving what are known as combinatorial auctions, where bidders in different locations can make offers on individual or multiple units up for sale. The goal is to maximize efficiency, enabling the greatest profits while limiting bidder frustration. In the case of the auction for Vietnamese rubber, the United Nations wanted to run an auction where bidders located around the world could log into the system, see leading bids on pallets from a number of different plantations, and enter bids for those they were interested in buying.

Plott designed the auction system to continuously solve what computer scientists know as the knapsack problem: given a knapsack of a certain size, which objects of various weights and values do you pack to maximize the collection's value while limiting its weight? Looking at the rubber auction, some bidders wanted individual pallets while others were interested in specific combinations. The system had to be able to solve a complex combinatorial optimization problem almost instantaneously, sifting through all of the different permutations and combinations to quickly determine the best fill for the collective knapsack.

Once programmers in Plott's group made the auction system a reality, Plott tested it in the lab to see how it fared. Participants in his test auctions were motivated by monetary rewards to try to purchase certain units for the best prices. As a result of these experiments, Plott discovered several aspects of the system that needed tweaking. For one, he found that the auction should allow not only bids that would become leading bids but lower offers as well. The latter bids remained as potential partners for succeeding bids that needed partners in order to become leading. Plott also found that to keep bids coming at a reasonable pace he needed to implement a timing system that involved two clocks—one counted down five minutes from the last bid submitted while the other counted down 15 minutes from the last change in leading bids. When either clock timed out, the auction would be over. The first clock encouraged bidders to make offers in a timely manner, and the second ensured that bidders weren't just making small concessions, waiting for others to give more—that they would actually get a deal done.

Plott remembers logging in to watch the actual auction play out in real time. "I was sweating bullets for the first few minutes," he says. "Here was this auction that I had created, that the UN had put its faith in, and only one bidder was entering bids."

Eventually new bids started rolling in, and the system worked beautifully, he says, attributing much of the auction's success to the sophistication of the software that ran the market and the experiments he conducted to work out the bugs.

"You can philosophize all you want, but you can't imagine exactly what has to be done until you actually see it," says Plott, who has also designed auctions to sell water rights, fleets of cars, the procurement of transportation services for getting disadvantaged students to school, and the rights to fish in certain areas off the coast of Australia, to name a few. "When you treat economics like a science—when you put in the time—you get long-term benefits."

Multistage Steps Up

As experimental economics has grown and developed as a field, so too has the level of complexity of the experiments its practitioners conduct. Many Caltech economists are now interested in complex systems that involve not only markets and economic decision making but also other behaviors and considerations such as voting, bargaining, committee deliberations, and abstract games.

In order to run lab experiments on such complex systems, researchers found about a decade ago that they needed a new modular software platform that could be customized to include any number of those considerations. As director of Caltech's Social Science Experimental Laboratory at the time, Tom Palfrey oversaw the development of this platform, known as Multistage.

"Multistage integrates all of these things that had been previously done as separate components," says Palfrey. "People would study voting alone, or people would study bargaining, or auctions, or markets. Our idea with this software was to pull these things together under a wrapper where you

could look at all of these things all at once along with their interactions."

In one study, Palfrey used the software to analyze what happens when people are allowed to buy and sell votes as they would commodities. Political scientists and economists have suggested such open trading of votes as a possible way to deal with the theoretical situation where a minority of voters cares intensely about an issue but is defeated by a majority of indifferent voters. But the notion of trading votes has remained controversial in the field, as some have suggested such a practice could lead to corruption.

In the lab, Palfrey gave participants a set amount of time to trade votes on an abstract issue. They could buy and sell votes freely, and each participant was assigned different monetary payouts for various vote outcomes, setting up a situation in which people sometimes had opposing preferences.

In the end, Palfrey and his collaborators found that prices for votes converged to equilibrium prices—those at which everyone in the market would cease trading, happy to stop buying and selling—and that those prices were determined by a single voter who valued the issue most. That meant that in an effort to accumulate a controlling share, one voter was always willing to pay a price that was higher than anyone else was willing to pay.

"The idea behind a market for votes is to allow the outcome to reflect intensity of preference," says Palfrey, "and it does that, but we found that it reflects only the intensity of preference of one person. So instead of being more like a democratic outcome, it turns out to be an outcome where one person basically becomes a dictator by buying the majority of votes."

Making a Good Match

Leeat Yariv (above) also used the Multistage software to look at an entirely different set of questions—those related to matching problems. These are situations in which people need to be paired with other people, positions, or institutions. The goal is to make so-called stable matchings—those where no one would prefer to be alone rather than paired, and no pair's members would prefer to be with one another over their respective matches. A well-known centralized matching system is the one that, following a fairly simple algorithm, pairs medical students with residency programs.

But there are also decentralized matching markets, where people act freely and try to make their own pairings. Think of the dating scene, for example, where any number of possible pairings is possible, and in which it is extremely difficult to say whether an optimal match has been made. For researchers, it is also hard to collect data that capture the whole decision-making process from beginning to end.

Yariv has studied this type of problem using two approaches. First, she identified a decentralized matching system that actually *does* track the kind of information she needs: the adoption process in the United States, specifically when aided by an online facilitator. An adoption facilitator serves as a channel through which potential adoptive parents can see information related to children up for adoption and apply to be their parents, giving birth mothers a pool from which to select.

Since 2004, Yariv and her collaborators have been working with data from one such facilitator to try to understand how decentralized markets operate. "Using the data, we could both estimate the model of matching and get at very basic things like the preferences people have for children's characteristics," she says.

What they found was a strong preference for Caucasians, girls, and babies who are closer to birth. "The findings make us think about how to design these processes better, so that more children are adopted. Now that we know the preferences, we can start thinking about how to redesign things," she says.

The data also showed that approximately 17 percent of accepted applications were from same-sex couples.

"These kinds of results offer some insight about the potential effect of policy," says Yariv. For example, in some states, same-sex couples are not allowed to adopt children. Had the facilitator that Yariv and her collaborators studied banned same-sex couples from its pool of applicants, the number of successful adoptions it made during the study would have dropped by 9 percent.

In tandem with the adoption study, Yariv and her colleagues, including Caltech professor of economics Federico Echenique, re-created centralized and decentralized markets in the lab, aided by the Multistage software. First they assigned each participant to be either a food (e.g., apple, banana, cherry) or a color (e.g., red, green, blue) and gave everyone a matrix of payoffs for potential pairings (e.g., apple–red = $5, banana–red = $3, banana–blue = $10). In the decentralized setup, participants were then allowed to make nonbinding offers to anyone in the market by entering offers online. For example, a red participant might get a note on his computer screen asking if he would like to match with banana, and would have to decide whether to accept that offer.

In the centralized setup, half of the participants—either foods or colors—were asked to input their offers sequentially. They were prevented from making offers to anyone who had already rejected one of their offers. The other half of the participants simply accepted or rejected the offers. With these restrictions in place, the system emulated what happens using an algorithm like the one governing the National Resident Matching Program.

In the end, the researchers found that participants managed to establish a stable matching nearly twice as often in decentralized markets relative to their centralized counterparts. This was wholly unpredicted by theory. Indeed, centralized clearinghouses are often put in place with the very goal of implementing stable outcomes.

It's Complicated

Ledyard points out that before Caltech's new software suite was developed, it would have been extremely difficult or impossible to test such intricate systems. "In order to run these complex markets in the laboratory we actually need more complicated software than what the NASDAQ needs to run its markets," he says. "We need to keep track of more things and we need to do it faster."

In his own group, Ledyard has developed additional software to study the problem of overfishing in fisheries—an issue that requires him to look not only at quantities of fish but also at environmental considerations and the effect of buyback auctions, where fishermen are invited to name a price that they would take to stop fishing, and some number of those fishermen are paid to take their boats out of the water.

Based on the results of his experiments, he has recently made concrete recommendations for how to improve buyback auctions, such as making them uniform-price auctions where fisheries let fishermen know that they will pay all of those leaving the water the same price—the highest bid that removes the desired number of boats, rather than their individual bids. This has been shown to produce more honest bidding and results in the removal of more boats than a traditional auction system. Ledyard hopes in the future to use the same software he has used for the fishing problem to study global-warming treaties—the bargaining processes involved, whether it makes sense to use cap-and-trade programs, and how to arrive at good policies.

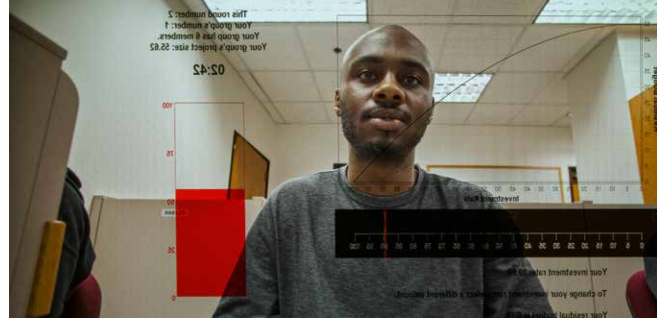
"The work in all of our groups is ongoing," says Ledyard. "But it would have been extremely difficult, if not impossible, to get started without the Moore Foundation's help." e&s

John Ledyard is the Allen and Lenabelle Davis Professor of Economics and Social Sciences.

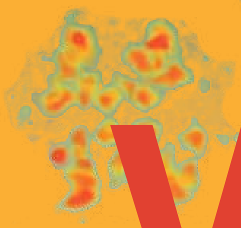
Tom Palfrey is the Flintridge Foundation Professor of Economics and Political Science.

Charles Plott is the William D. Hacker Professor of Economics and Political Science and the founder and director of the Laboratory for Experimental Economics and Political Science at Caltech.

Leeat Yariv is a professor of economics and the director of the Social Science Experimental Laboratory at Caltech.



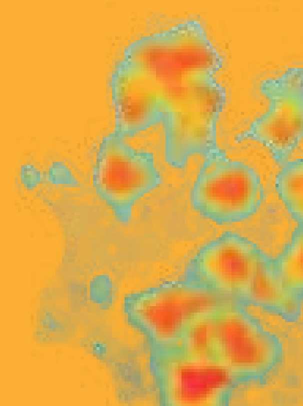
Subjects at Caltech's Social Science Experimental Laboratory (SSEL) participate in economic studies using the Multistage software developed at the Institute.

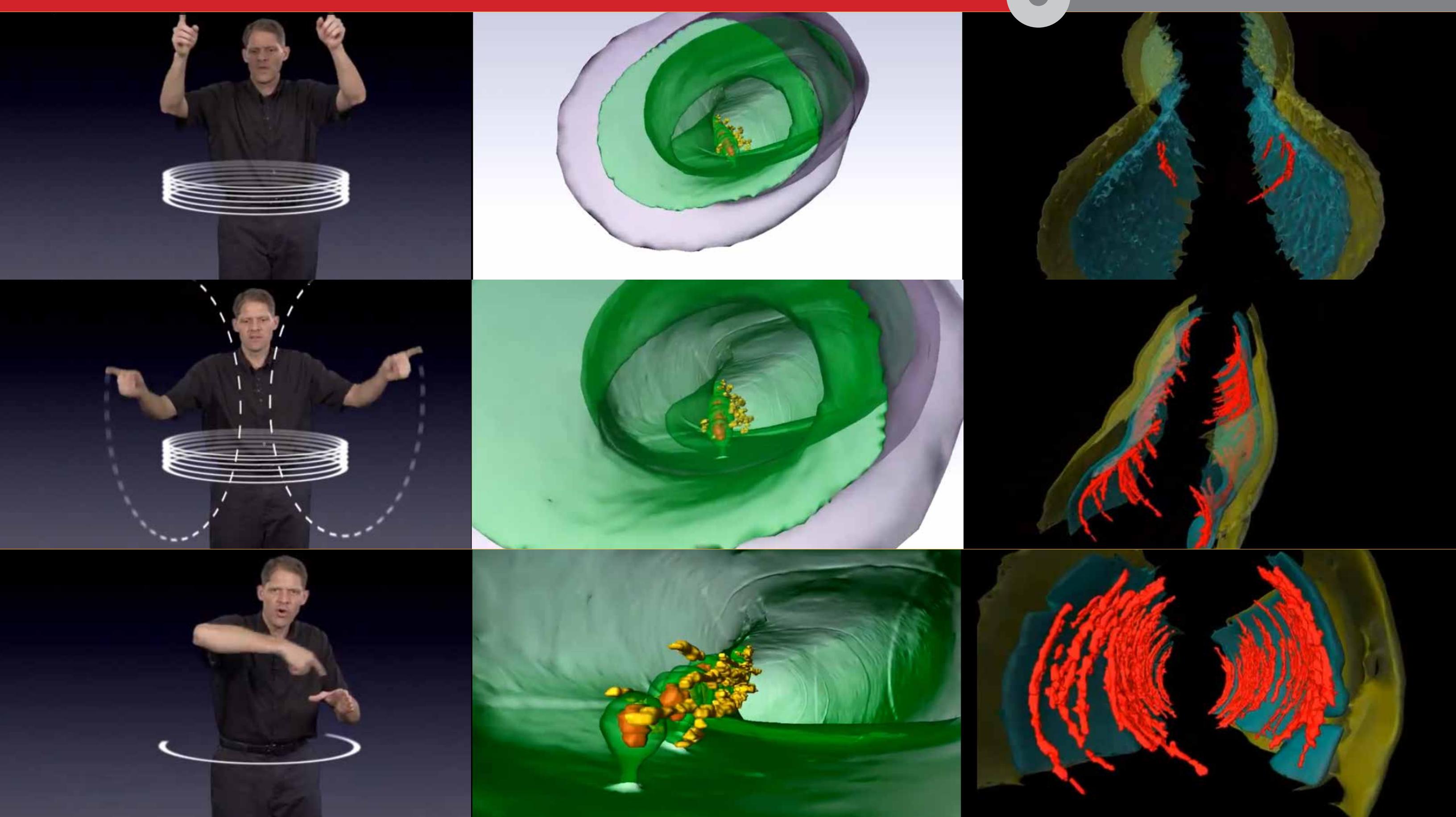


Viral Videos

(And Bacterial Ones, Too)

by Katie Neith





Grant Jensen is a high-powered movie producer. You won't see his name on any of this fall's Hollywood blockbusters, but in the field of cell biology, he has revolutionized the view that researchers, and even the curious public, get of the insides of cells. He does this through the innovative use of a digital camera and specialized electron microscope, which together enable a field called cryo-electron microscopy, or cryo-EM.

Now, he's taking what he's learned over the past 13 years using cryo-EM and sharing it through a series of online videos that serve as visual textbooks to teach to the world the skills and knowledge needed for cryo-EM studies.

"The nature of our work is very visual," says Jensen, a biologist who is one of just a handful of experts in this growing field, in which the electron imaging of cryogenic samples allows scientists to image biological specimens in as close to a natural, or native, state as possible.

By stringing together high-resolution microscope snapshots taken of such samples from various angles, Jensen and his team have been able to create three-dimensional moving pictures of cells, viruses, and bacteria. "My lab members and I have been really thrilled with the impact of the movie presentations we've put online with our papers," Jensen says.

Being able to image, in their native state, the macromolecules inside cells has provided the group with new information on the architecture of cell walls, on how cells determine their shapes, on how they move, on how they metabolize and store nutrients, and on how they fight each other.

"We've also discovered, just by seeing cells better than has ever been possible, entirely new structures in bacteria and viruses," Jensen says. "The images we've been able to produce have also revealed completely new ideas about the evolutionary relationships between different families of bacteria and bacterial secretion systems and phages. We've also used the microscope to study the structural biology of HIV. Excitingly, we've begun to understand structures inside the cell related to viral entry and egress."

Special Effects

It all started by taking a chance. As part of the Moore Foundation's 2001 gift to Caltech, the Institute's scientists were tasked with identifying potential projects for funding, especially those that might be considered "high risk, high reward."

"One of the things the faculty realized was that, in the future, we really ought to be doing cellular imaging by electron microscopy. So the administration took some of the Moore money and bought the world's best electron microscope at the time," says Jensen.

That great microscope was a state-of-the-art FEI Polara transmission electron microscope, and it helped Jensen decide to join Caltech's faculty in 2002.

The Polara uses an electron beam to illuminate samples that have been flash-frozen into a fixed state and kept below –150 degrees Celsius. This process eliminates much of the damage that can be done in traditional microscopy, for which samples must be fixed, embedded in plastic, sectioned, and stained. The process of freezing the samples instead captures cells in action, binding them in a layer of transparent ice.

"At the time that the microscope was purchased, and when all these people moved to Pasadena and aligned their lives with mine, no one knew what we would discover if we looked inside cells in this new way," Jensen says. "So it would have been totally impossible to fund the microscope through traditional pathways."

That's because nailing down funding for new research, especially when it employs expensive and unproven instrumentation, often involves a sort of chicken-or-egg problem, he says. If an institution decides it needs to do the kind of high-end cryo-EM that he's made such good use of, they need two things simultaneously: an expert and a microscope. If they don't have the microscope, it's hard for them to recruit an expert. And if they don't have an expert, they can't write the grants to get a microscope.

"The Moore Foundation trusted Caltech that they would use their money wisely, allowing the Institute to overcome this barrier—they solved the chicken-or-egg problem," says Jensen.

Early success using the microscope—such as revealing, for the first time, certain structures inside bacteria, and individual HIV-1 viruslike particles—then led to additional federal grants, an appointment for Jensen as a Howard Hughes Medical Institute investigator, and an ever-expanding team. Which is exactly what unrestricted funding is meant to do: seed research that can then garner funds and resources from more traditional sources.

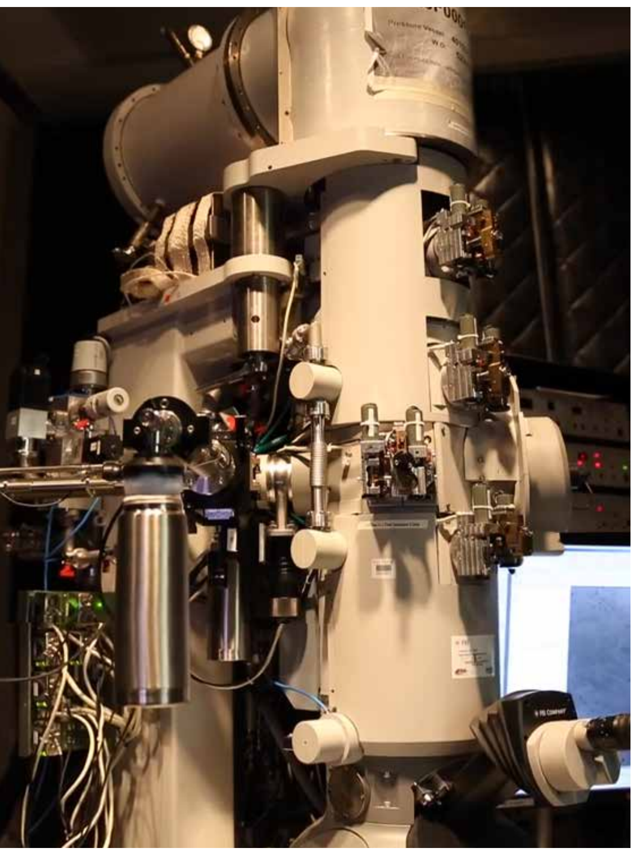
"As we had continued success, some of people in the lab who were doing cutting-edge research decided to stay on with the team longer. Their expertise, experience, and abilities allowed me to expand the team even further because they were able to train and guide the new members," says Jensen. "After five or six years it became very clear that imaging cells with cryo-EM was opening dramatic new windows into the cell, and that attracted just the very best structural biology postdocs. The microscope was absolutely critical to their recruitment. It nucleated the whole effort."

Some of the people he's recruited along the way are computer scientists and biologists who are also interested in graphics and visualization.

"Because of that, we've found ourselves both with 3-D data and people who were interested in trying to depict that data with computers in the most useful way possible," says Jensen.

The results can be seen on his lab's website, where you can witness a cholera-causing bacterium delivering a toxin to its competition; see the unique structures of a spirochete—a type of bacteria that is part of the termite's microbiota—and the way it moves through termite guts; and gain an inside view of HIV development.

"We've seen things that no one even knew existed, inspiring completely new directions of inquiry in bacterial cell biology," says Jensen.



A close-up of the Polara electron cryomicroscope that Jensen uses shows the front of the column, with the sample loading chamber on the left and the aperture controls on the right.

Required Viewing

Now Jensen is hoping to spread the knowledge he's gained through watching movies by making movies; in February 2015 he released free and publicly available video-recorded lectures on the uses of cryo-EM so that others can be empowered to make their own discoveries.

"There's been a big burst of interest from structural biologists and cell biologists who want to learn about cryo-EM," says Jensen. "I think my online course is going to help people around the world get started in the field on whatever day they decide they want to learn about it. The videos are particularly needed because we have a lot of people who want to learn the field, and a small number of people who can teach it. It's not like your average biochemistry class, where every college has a teacher."

In addition to offering a comprehensive online learning platform for professionals in the field, Jensen is using the video lectures in his classroom instruction as well. It's a pedagogical choice that has led to some surprising results. Earlier this year, for instance, he asked his students to watch the lectures at home and then come to class prepared to review certain study questions in front of their peers.

"While it was a little unusual at first for the students to be on the spot, the class became really talkative," says Jensen. "All of a sudden the whole class was very open and much more communicative. It completely broke the teacher-student barrier to have the students at the board."

The students weren't the only ones for whom the experience was disorienting and exciting.

"It turned out to be challenging for me because I no longer controlled everything that was going to be presented that day," he continues. "I think that made the students even more comfortable because now all of us were standing in front of the group exposing the boundaries of our knowledge. It democratized the classroom."

Jensen recognizes that the future of teaching in science and math will involve—and possibly revolve around—these kinds of recorded lectures. And in his field in particular, he believes online course instruction is a better tool than any textbook could be.

"Things can move in an online class," he explains. "I can build a diagram element by element, explaining each piece of it. That's very difficult to do in a textbook figure."

Given his track record of success in all things cryo-EM so far, it's probably fair to say Jensen and his online classes are moving in the right direction.

"The bet that people made in buying this microscope, and in coming to join my team, has paid off richly in ways that no one could have even anticipated," says Jensen. "In part because of the Moore investment, cryo-EM is having a growing global impact on many different levels. And we're just getting started." e&s

Grant Jensen is a professor of biophysics and biology at Caltech and an investigator with the Howard Hughes Medical Institute (HHMI). The National Institutes of Health, the Beckman Institute, HHMI, and the Gordon and Betty Moore Foundation help support his work in cryo-electron microscopy.

More information on Jensen's cryo-EM online lectures can be found at cryo-em-course.caltech.edu.

In 2002, when Grant Jensen arrived at Caltech, the Institute had **ONE** of only a few high-end cryo-electron microscopy facilities in the world.

His lab has published nearly **100** studies featuring results from the technology.

At Caltech alone, more than 27 faculty members now use the cryo-electron microscopy facility for a variety of research projects.

Jensen has trained 20 postdocs in cryo-EM.

Jensen collaborates with some **40** microbiologists around the world to address key questions using cryo-EM.

OVER **40** high-end cryo-EM labs are now established across the globe. FIVE are led by former postdocs of Jensen's who now have their own labs in Singapore, Switzerland, England, Canada, and the United States.

Funding agencies like NIH, NSF, and HHMI have now begun to allocate resources for cryo-EM. "Many institutions have chosen to invest large sums of money in microscopes like ours as people have seen what they can do," says Jensen.

48 instructional videos in cryo-EM are now available on numerous online platforms. Jensen's introductory video alone received more than 2,300 views in its first two months online.

Jensen says he's **100 percent** sure he will continue to incorporate his online lectures into his classroom teaching.

AN INTERNATIONAL SENSATION

Ready,

Set, Explore

by Jon Nalick

A restless experimenter, John Eiler cannot resist uncharted territory—even when that happens to be on another planet or billions of years back in time.

In recent years, the geochemist has partnered with colleagues in disparate scientific fields to make discoveries in paleontology, archaeobiology, atmospheric chemistry, climatology, martian geology, and more. Along the way, he has helped develop and refine instruments that reveal previously hidden facets of chemistry, and opened up new areas for scientific exploration.

"My inclination is to be constantly in motion and working in a segment of the scientific community where I can create something that really feels new to me," Eiler says. "So my career has been basically composed of episodes in which I pick something that interests me, then really burrow into it and try to create something substantial. I follow it up with support research, but pretty soon, I'm ready to pack my bags and go do something else."

Last year alone, "something else" included examining coral growth for hints about the connection between historical glacial cycles and changes in carbon dioxide (CO_2) levels in the deep ocean, and confirming the presence of sulfate-reducing microbes in 2.5-billion-year-old sediments.

The main tool in Eiler's kit that permits him to plumb new areas so effectively has been the analysis of isotopic clumping, a novel chemical analysis technique he developed to answer otherwise impenetrable questions. The technique exploits subtle differences in chemistry between the isotopes of a given element—such as carbon. (Isotopes are forms of the same element that differ only in the number of neutrons they contain).

For example, the most common form of carbon, carbon-12, contains six protons and six neutrons, while the rarer carbon-13 contains six protons and seven neutrons. Despite the differences in their number of neutrons, isotopes of a given element are generally thought to be chemically identical: any isotope of oxygen will behave exactly the same way as its peers in terms of what it will interact and combine with. Even so, the isotopes differ in mass, which makes their bonds with other atoms slightly more or less stable, subtly changing reaction rates and isotopic preferences for concentrating in one molecule or atomic site versus another.

The key phenomenon underlying Eiler's work on isotopic "clumping" is that heavier isotopes tend to bind to one another, or clump together, more strongly at lower temperatures and more weakly at higher temperatures. Thus, a measurement of the extent of "clumping" of oxygen, carbon, or hydrogen isotopes in a given sample often constrains the temperature at which a sample formed (though other sorts of chemical and physical effects might also change the proportions of "clumps").

The concept seemed so unlikely when he started talking about it in 2003 that at scientific conferences he was often met with blank stares from attendees. "I'd look out at an audience, which was totally quiet, and realize they didn't have any idea what I was talking about," he remembers. "They'd just think I was talking about a measurement that sounds impossible."

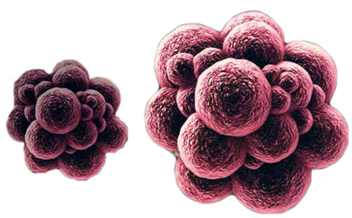
But Eiler immediately comprehended the potential power of the technique: by focusing on the isotopic structure of compounds instead of simply tallying their total isotopic inventory (as is commonly done), he could glean hitherto inaccessible information. The difference is akin to that of seeing letters jumbled in a bowl of alphabet soup versus seeing the same letters arranged in a newspaper headline.

> I know we're going to return materials from Mars, and I bet we will find at least one organic molecule in them. And immediately we'll be faced with a difficult question—when you have a simple amino acid sitting on the table in front of you, how do you know what made it?

Much of Eiler's work was made possible by two Moore Foundation gifts. An $8.8 million gift in 2006 created the Center for Geochemical and Cosmochemical Microanalysis, which Eiler directs. The center's resources include two secondary-ion mass spectrometers for analyzing elemental and isotopic abundances, and a facility for developing highly sensitive new instruments to explore geochemistry. An earlier $13 million gift in 2004 created the Tectonics Observatory, which, though now closed, still houses the magnetic sector mass spectrometers he relies on for light-element isotopic analysis.

DINO TEETH AND METHANE FORMATION

Like many scientists, Eiler's fascination with the natural world began as a child. At age six, his curiosity about paleontology and history was apparent in a school report he titled "Dinosaurs—Roar!" Little did he know that 38 years later, his second attempt at a dinosaur paper would make headlines.

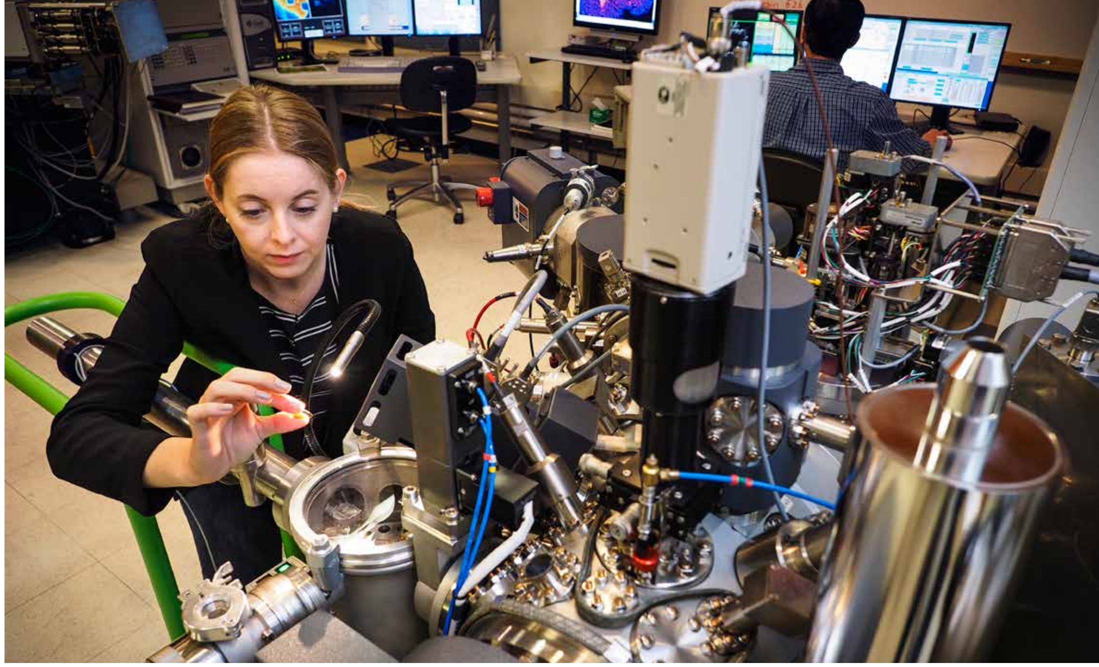


In 2011, Eiler led a team that, for the first time, provided hard physical evidence that dinosaurs, rather than being cold-blooded creatures as paleontologists long thought, maintained body temperatures that approximate those of contemporary mammals. For the study, which was published in *Science* and made a splash in the media, his team examined the rare isotopes carbon-13 and oxygen-18 in bioapatite, a mineral found in teeth and bone. Because carbon-13 and oxygen-18 bond to one another in bioapatite at a higher rate at colder temperatures, measuring the clumping of these isotopes directly shows the temperature of the environment in which the mineral formed. In this case, the body temperatures at which the minerals formed inside the dinosaurs studied—*Brachiosaurus brancai* and *Camarasaurus*—were found to be about 38.2 degrees Celsius and 35.7 degrees Celsius, respectively. Subsequent work applied the same tools to carbon-oxygen bonds in the eggshells of several dinosaurs, demonstrating that relatively small ones had significantly lower body temperatures, intermediate between those of modern reptiles and mammals, suggesting the apparent "warm bloodedness" of large dinosaurs may have been due to their great size rather than a metabolism resembling modern mammals.

True to form, however, Eiler did not rest on his laurels. He jumped into several other projects that would lead to a flurry of papers in 2014. After tackling long-lost dinosaurs, Eiler teamed up with former Caltech graduate student Daniel A. Stolper (PhD '14) to develop a new technique for helping to determine how, and to some extent, where, a sample of natural methane was formed. Methane—a single carbon atom bound to four hydrogen atoms—forms through a variety of biological and nonbiological processes and under a wide range of conditions, but simply knowing its chemical formula provides no clues as to its origin.

Methane is produced by living organisms at temperatures below about 80 degrees Celsius, while methane created through the thermal breakdown of buried organic matter occurs at temperatures as high as 200 degrees Celsius. Being able to determine the temperature at which a methane sample formed can therefore reveal clues to its origin—an insight that served as a starting point for the study. Using a mass spectrometer that the team designed in collaboration with Thermo Fisher Scientific, the scientists examined the clumping of carbon-13 and deuterium (hydrogen-2) in gas samples created in the laboratory under known conditions to confirm the method's accuracy.

The team then analyzed samples of methane from the Haynesville Shale—a rock formation and methane reservoir that stretches across three Southern states—and found that their results closely matched the reservoir's temperature. They also found that methane formed biologically by oil-eating microbes returned temperatures within a few degrees of the temperatures—around 44 degrees Celsius—of the sampling locations. Additional tests validated the technique as an effective geothermometer, which Eiler says can have important applications in helping to determine, for example, the origin and migration of underground oil as a groundwater pollutant. Subsequent work by Stolper, Eiler, and other colleagues, published in April, demonstrated that this tool can determine mixing ratios of biogenic



Catherine Macris, a postdoctoral scholar working in Eiler's lab, inspects a polished slice of a tektite—a natural glass formed as a result of high-velocity impacts into Earth's crust—prior to loading the sample into one of Caltech's two secondary-ion mass spectrometers.

and thermogenic gas in places where the two sources mingle, and also found evidence that in some conditions biological methane-producing reactions can wildly violate the usual patterns of clumping, leading to distinctive isotopic fingerprints that may give clues to the mechanisms of microbial metabolism.

CORAL REEFS AND MARS MOLECULES

Eiler also contributed to a 2014 study concerning climate change, which examined the connection between historical glacial cycles and CO_2 levels in the deep ocean. Because ice sheets generally shrink as CO_2 levels rise, and vice versa, the team hypothesized that the deep ocean—which stores 60 times more inorganic carbon than does the atmosphere—must play a crucial role in these cycles.

Along with Professor of Geochemistry and Global Environmental Science Jess F. Adkins, leader of the project, and Dreyfus Postdoctoral Scholar in Geochemistry Nivedita Thiagarajan, Eiler analyzed the calcium carbonate skeletons of corals collected from one mile below the surface of the North Atlantic. The corals were built up from 11,000 to 18,000 years ago out of CO_2 dissolved in the ocean. Again using clumped isotope thermometry to look at carbon and oxygen isotopes in the calcium carbonate, the group was able to determine the temperature of the water in which the coral grew. The evidence showed that the deep ocean began to warm rapidly before the start of a major climatic shift 14,600 years ago when ice sheets—which had covered a large portion of the earth for about 100,000 years—retreated to their modern ranges. The results help elucidate the underlying mechanisms of climate change and may help us predict how climate may change in the future.

Looking to his prospective research plans, Eiler says he hopes to adapt what he has learned investigating the histories and origins of fairly large molecular structures.

"Instead of measuring one special property, like a certain isotopic combination in methane that tells us its formation temperature, we'll try to make measurements where you observe 100 different combinations of isotopes in a single molecule and read back from it information of enormous complexity—maybe its conditions of formation, or the conditions it was stored at, or what substrate it was formed from, or the exact chemical reaction mechanisms by which it was synthesized," he says.

In the short term, he hopes to develop a measurement that can distinguish complex molecules made by life from those same molecules made by nonbiological processes.

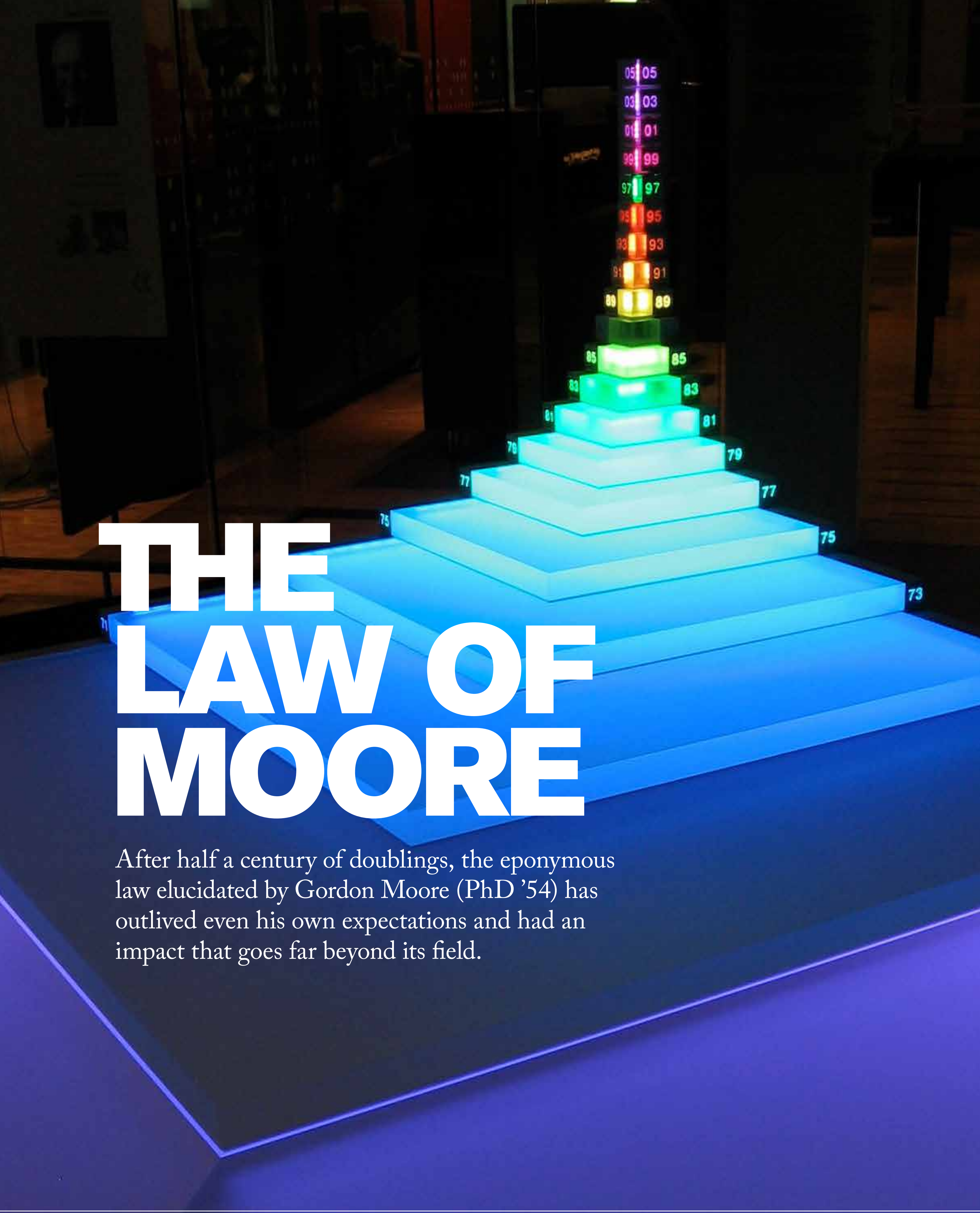
"I know we're going to return materials from Mars, and I bet we will find at least one organic molecule in them," he explains. "And immediately we'll be faced with a difficult question—when you have a simple amino acid sitting on the table in front of you, how do you know what made it?"

According to Eiler, it's actually very difficult to tell because there are many processes that make what we normally think of as biomolecules—they occur in space, they get made in rocks, they get made in hydrothermal vents, and so on. But if there was a way of reading from the isotopic structure a very specific description of how that molecule was assembled and from what and under what conditions, that would be helpful.

"We'd have measurements that allow you to say, 'That is an amino acid that fell on Mars out of the sky on a meteorite,'" he says. "Or, 'That's an amino acid that was synthesized in a hydrothermal vent in the crust of the martian surface.' Or 'That was a monster that lived on Mars and this is its amino acid.'

"If we can reach that goal, we will have landed ourselves in a place where we can freely ask similar sorts of questions about all kinds of things: biomedically important compounds in your body, drug compounds, environmental forensics—all kinds of things that involved the history or origin of molecules of moderate complexity," he continues. "I don't know if we'll reach that goal, but it feels important to me. It's exciting to me. It's what I want to explore." e&s

John Eiler is the Robert P. Sharp Professor of Geology and professor of geochemistry.



THE LAW OF MOORE

After half a century of doublings, the eponymous law elucidated by Gordon Moore (PhD '54) has outlived even his own expectations and had an impact that goes far beyond its field.

It began quietly, with a 1965 article in *Electronics* magazine. But as if following Moore's Law itself—the prediction that states that the number of transistors that could fit on a single silicon chip would double approximately every two years—the concepts in that article grew quickly, exponentially, in import and influence.

Gordon Moore (PhD '54) started that article, titled "Cramming more components onto integrated circuits," with other predictions that are equally—and almost spookily—accurate today. "The future of integrated electronics," he wrote, "is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas."

This year, as Moore's Law turned 50, many people turned to look at what it has meant for not just the computer industry, but for our world. In May, the *New York Times* columnist and Pulitzer Prize–winning author Thomas Friedman talked about the law with Gordon Moore himself at San Francisco's Exploratorium at an event hosted by Intel (the company Moore cofounded in 1968) and the Gordon and Betty Moore Foundation.

During that interview, Moore spoke of the *Electronics* article and the birth of his law, saying, "I had no idea that it was going to turn out to be a relatively precise prediction, but I knew that the general trend was in that direction."

When asked if he was surprised by how long Moore's Law has lasted, Moore replied, "Oh, I'm amazed. The original prediction was to look at 10 years, which I thought was a stretch. This was going from about 60 elements on an integrated circuit, to 60,000—a thousandfold extrapolation over 10 years. I thought that was pretty wild. The fact that something similar is going on for 50 years is truly amazing."

At Caltech's 121st commencement ceremonies, cultural anthropologist Genevieve Bell—who is, most notably, a vice president at Intel and an Intel Fellow—spoke about the wider impact of Moore's Law. Her address to the graduates, which follows in part, put into context its human, as well as its technological, import.

The class of 2015 has much to celebrate, and you'll remember this date—trust me on this, this will become a metric in your life—and you'll measure your progress against it for years to come. But for me, this is a significant date but for a very different reason . . . . This year marks the 50th anniversary of Moore's Law. The logic of Silicon Valley, the law that predicts the rate of technology change and thus innovation was born 50 years ago this April. It's older than me (just), it's older than many of you, I hope, and it was imagined in a time when the world looked really different. There was no web, no Internet, no talk of big data, no Internet of things, no wearable technology, no YikYak, no selfie sticks, no Facebook. Astonishing, right? But there was the integrated circuit and a man named Gordon Moore. And you all know he graduated from here with a PhD in chemistry and a minor in physics. So this is as much your history and legacy as it is mine.

And in 1965, ten years after Dr. Moore graduated from here, a popular trade magazine approached him and asked him to speculate about the future of his industry. Looking back over a decade of rapid transformation, he predicted that integrated circuits, the building blocks of contemporary computing, would enjoy an unprecedented rate of growth. He wrote that the number of transistors on a densely integrated circuit would double every two years for at least the next decade. Basically integrated circuits would continue to get more powerful on a knowable rate. It was then a bold statement of engineering, and 50 years on, it's an observation that's continued to predict the rate of technological improvement, which is in and of itself kind of amazing.

But, for me, the thing that's more important is that Moore's Law is also a promise about the state of the future. After all, this is not a law describing the natural world, but rather the way we choose to configure it. In effect, it's a promise of a world that we better with every passing year. It's the promise of room to grow, room to imagine; of continuous innovation.

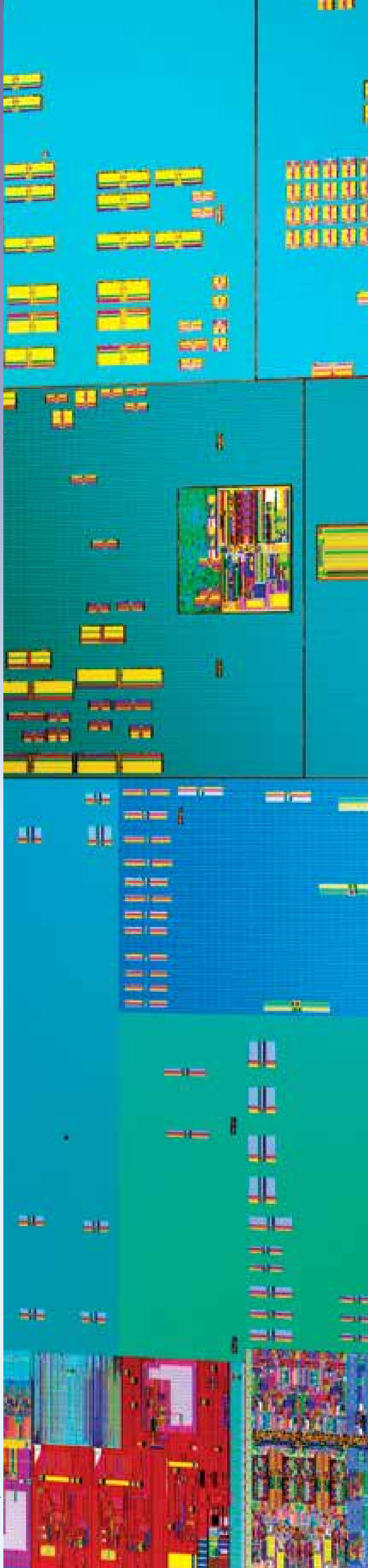
And in Gordon Moore's original article, he also articulated why this innovation was important. For him it wasn't just technology for technology's sake. He wrote, and I want to quote here because it's kind of remarkable, "Integrated circuits will lead to wonders such as home computers"—remember, 1965—"or at least terminals connected to a central computer, automatic controls for automobiles, and personal portable communication equipment." He then added, "The electronic watch only needs a display to be feasible today." Maybe 50 years off the pace on that one, but still.

Again, think about it. How many things do we hear today that you imagine will actually be true in 50 years? Can you sit there and tell me what the world will look like in 2065? I know I can't, and it's partly my job. So there's something sort of amazing about it, right?

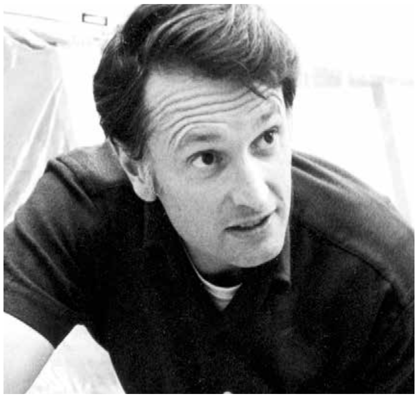
But Dr. Moore didn't stop at simply imagining that world. Instead he took a step that I think many of us will recognize, and I hope some of you will do, which is that he and his colleagues Robert Noyce and Andy Grove left the company they were working in, Fairchild Semiconductor, and started their own company. They backed themselves. They made in some ways one of Silicon Valley's original start-ups. They conceived a big idea and they founded Intel on it. Silicon Valley grew up out of this idea and out of the computing power it unleashed; so did many other technology centers and many other companies. In fact, all of us have grown up in that world of wonders that Dr. Moore imagined. Every time you post a photo, send an email, flirt long distance—which I suspect some of you do—Skype, send remittance payments, use hashtags to participate in debates, back political candidates and then wonder why they're still emailing you (we all know this one and it's only gonna get worse), worry about the venom in the comments sections of every paper we read, fund someone's big idea on Kickstarter, binge on *Game of Thrones* for a whole season, or—my personal favorite—share that video with the cat in a shark suit on a Roomba being chased by a duck, because you can, you are living in the world that Dr. Moore and all of his contemporaries built for us. They have given us 50 years of technological innovation and change. e&s

Friedman interview video:
bit.ly/1M9nInm

Genevieve Bell commencement address:
bit.ly/1Ul8gpz



John H. "Jack" Richards 1930–2015



John H. "Jack" Richards, a professor of organic chemistry and biochemistry at Caltech whose research was focused on gaining a molecular understanding of the mechanisms of protein function, passed away on April 23, 2015. He was 85 years old.

Richards used altered proteins obtained from the deliberate mutation of DNA—a process called site-directed mutagenesis—in combination with recombinant and cloning techniques, as well as chemically synthesized polypeptides (chains of amino acids) and their derivatives, to study the mechanisms by which proteins act as catalysts to perform the chemical reactions necessary to life.

Among the proteins of particular interest to Richards were proteolytic enzymes that break apart other proteins; enzymes called lactamases that endow some microorganisms with antibiotic resistance; and DNA polymerases, the enzymes that build DNA molecules by assembling nucleotides.

Richards was born on March 13, 1930, in Berkeley, California, and earned a BA in 1951 and a PhD in 1955, both from UC Berkeley. He came to Caltech in 1957 as an assistant professor. Richards spent the rest of his career at the Institute and was the chair of the faculty from 1991 to 1993.

Richards also embraced his role as an educator and acted as a mentor to generations of undergraduate and graduate students, as well as to faculty, during his nearly six decades at Caltech.

"Jack was a coadvisor for my thesis work and an incredible mentor. He joyously encouraged and supported risk taking and strongly influenced my entry into the protein engineering field," says Stephen Mayo (PhD '88), Caltech's William K. Bowes Jr. Leadership Chair of the Division of Biology and Biological Engineering and Bren Professor of Biology and Chemistry.

Richards is survived by his second wife, Minnie McMillan. Richards also leaves behind four daughters from his first marriage (to Marian King), Kathleen, Jennifer, Julia, and Cynthia; and four grandchildren.

To learn more Jack Richard's life and work, visit caltech.edu/news/john-h-richards-1930-2015-46693

We asked alumni: If you had **NO LIMITS,** what would you do, build, or explore? Here's what some of them came up with.

Design business systems to **MAKE THE WORKFORCE ALL-INCLUSIVE**. We need to return to the ethos that everyone has a place in society.

RELOCATE TO RAPA NUI (Easter Island) and study the petrology of the igneous rocks that make up the island.

IMMORTALITY, BABY!

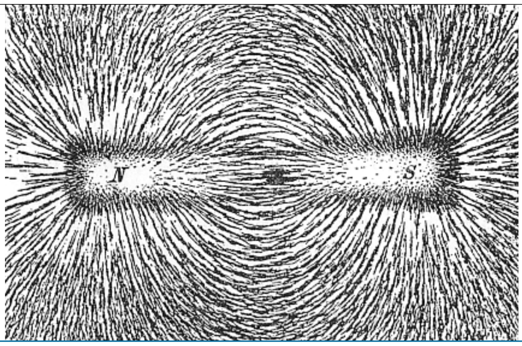
DO THE COLONY SHIP THING—to actually head out for the biggest and baddest road/space trip ever. The first manned Mars mission is looming, and I'm betting a few will go.

I would develop a form of Velcro that separates noiselessly, and then use it to replace **ALL OF THE WORLD'S BUTTONS**, especially on shirts.

Visit the nearest massive black hole and **JUMP IN.**

Explore the role of **QUANTUM ENTANGLEMENT** in biological systems, including the brain.

Perfect **MAGNETIC FUSION** power generation.



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