IEEE
SPECTRUM

FOR THE TECHNOLOGY INSIDER | 06.14

50th ANNIVERSARY ISSUE 1964-2014

THE FUTURE WE DESERVE

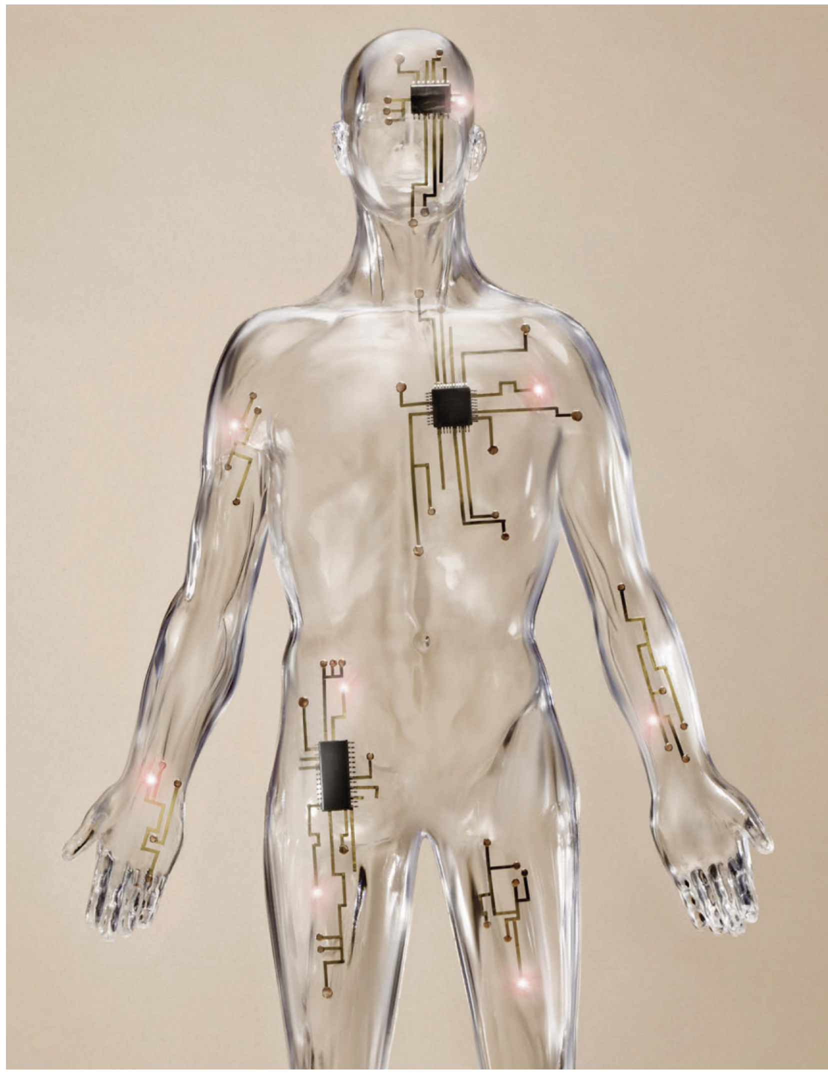
BRIGHT SCENARIOS FOR EIGHT OF TODAY'S HOTTEST TECHNOLOGIES
PLUS WHAT COULD POSSIBLY GO WRONG?

IEEE

CLICK HERE TO ACCESS THE JUNE ISSUE OF the institute

IEEE SPECTRUM 1964 / 2014

FEATURES_06.14



SPECIAL REPORT

THE FUTURE WE DESERVE

21 We don't know precisely what the next 50 years will bring. But we have an excellent idea of what will be possible, and we know what we hope will happen. So here are scenarios for eight of the most promising of today's technologies. If they develop along the lines we describe, we'll get the future we deserve.

PROP STYLIST: ROBIN FINLAY

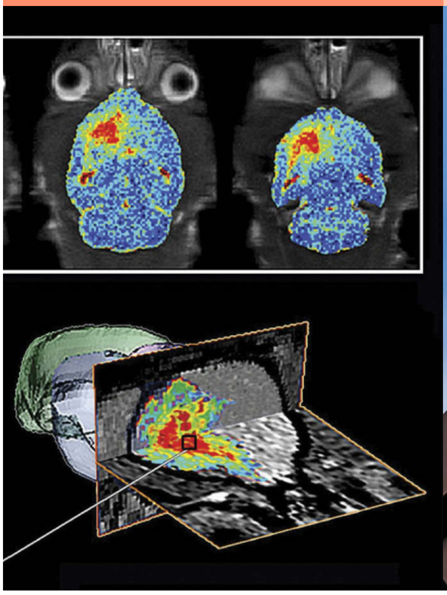
On the Cover **Illustration for *IEEE Spectrum* by Carl DeTorres**

PHOTOGRAPH BY Adam Voorhes

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page
Qmags THE WORLD'S NEWSSTAND®

DEPARTMENTS_06.14

IEEE SPECTRUM



FROM LEFT: HAO-LI LIU/CHANG GUNG UNIVERSITY; SWISS FEDERAL OFFICE OF TOPOGRAPHY; GEORGIA INSTITUTE OF TECHNOLOGY

Online

Spectrum.ieee.org

Videos of the Future
Meet Chris Harrison of Carnegie Mellon and see the future of augmented reality; get inside the mind of Google Glass pioneer Thad Starner [above]; and choose your own questions in an interactive video with renowned physicist Freeman Dyson.

ADDITIONAL RESOURCES

Tech Insider / Webinars

Available at spectrum.ieee.org/webinar

- Groundbreaking Smart Polygeneration Microgrid Project: University Campus of Savona, Italy—5 June
- The Use of High Performance Computing in Multiphysics Modeling—12 June
- Getting It Right the First Time: Three Ways Requirements Management Can Help Save Time and Money—17 June

- **IBM RATIONAL SMARTER PRODUCTS**
http://spectrum.ieee.org/static/ibm-rational-smarter-products
- **IBM RATIONAL INDUSTRY SOLUTIONS LIBRARY**
http://spectrum.ieee.org/static/ibm-rational-industry-solutions-library
- **WHITE PAPERS**
http://spectrum.ieee.org/whitepapers

The Institute

Available 06 June at theinstitute.ieee.org

SMART CITIES This special issue of *The Institute* focuses on projects that are making cities smarter, more efficient, and maybe even happier. IEEE is lending a hand through its Smart Cities initiative, in which members work with cities such as Guadalajara, Mexico, to implement technologies that can solve local problems.

Q&A WITH THE CANDIDATES Frederick Mintzer and Barry Shoop, who are vying for 2015 IEEE president-elect, answer members' questions and share their plans for the future of the organization.

EVALUATING RESEARCH Gianluca Setti, vice president of IEEE Publication Services and Products, explains why IEEE has issued new guidelines for assessing the true impact of research articles.

IEEE SPECTRUM
(ISSN 0018-9235) is published monthly by The Institute of Electrical and Electronics Engineers, Inc. All rights reserved. © 2014 by The Institute of Electrical and Electronics Engineers, Inc., 3 Park Avenue, New York, NY 10016-5997, U.S.A. Volume No. 51, issue No. 6, International edition. The editorial content of IEEE Spectrum magazine does not represent official positions of the IEEE or its organizational units. Canadian Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40013087. Return undeliverable Canadian addresses to: Circulation Department, IEEE Spectrum, Box 1051, Fort Erie, ON L2A 6C7. Cable address: ITRIPLEE. Fax: +1 212 419 7570. INTERNET: spectrum@ieee.org. ANNUAL SUBSCRIPTIONS: IEEE Members: $21.40 included in dues. Libraries/institutions: $399. POSTMASTER: Please send address changes to IEEE Spectrum, c/o Coding Department, IEEE Service Center, 445 Hoes Lane, Box 1331, Piscataway, NJ 08855. Periodicals postage paid at New York, NY, and additional mailing offices. Canadian GST #125634188. Printed at 120 Donnelley Dr., Glasgow, KY 42141-1060, U.S.A. IEEE Spectrum circulation is audited by BPA Worldwide. IEEE Spectrum is a member of the Association of Business Information & Media Companies, the Association of Magazine Media, and Association Media & Publishing. IEEE prohibits discrimination, harassment, and bullying. For more information, visit http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html.

PHILIP T. METZGER

BACK STORY_

Planting a Flag

WHAT'S IT LIKE to plant your feet in moon dust? Earlier this year, Associate Editor Rachel Courtland got a chance to find out.

Courtland traveled to Swamp Works, a laboratory at NASA's John F. Kennedy Space Center, in Florida, to research a story on the future of space exploration for this month's special issue. There she was allowed to step inside the facility's Big Box—a glass-walled room packed with 120 metric tons of powdered basaltic rock that stands in for lunar soil.

The rock, waste from a mining operation in Arizona, was selected for its moon-dust-like mechanical properties. The engineers and physicists at the laboratory use it to test robotic systems, and they let Courtland step inside to see what it was like.

Though she was boldly going where no journalist had gone before, safety was on Courtland's side. For one thing, true lunar regolith is replete with glassy, suit-shredding shards left by countless asteroid impacts and never smoothed by wind or water. The "lunar simulant" at Swamp Works doesn't have those sharp pieces, but it's still considered a health hazard. The dust particles are small enough to inhale deep into the lungs, and they're too big for the body's immune system to dislodge. So Courtland was allowed into the box only after being outfitted with a Tyvek suit, gloves, boots, and a battery-powered respirator.

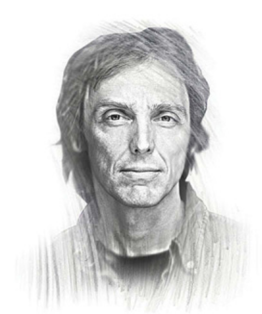
Once inside, she took a few bounding, Apollo-inspired steps, planted an IEEE flag, and tried digging into the surface with a shovel. How did it feel to be in there? "Otherworldly," Courtland declares. "Like walking on a giant mountain of talc." ■

06.14

CITING ARTICLES IN IEEE SPECTRUM *IEEE Spectrum* publishes an international and a North American edition, as indicated at the bottom of each page. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, Dataflow is in *IEEE Spectrum*, Vol. 51, no. 6 (INT), June 2014, p. 84, or in *IEEE Spectrum*, Vol. 51, no. 6 (NA), June 2014, p. 100.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

CONTRIBUTORS_



Philip Ball

Ball holds degrees in chemistry and physics and was a physical sciences editor at the journal *Nature* for many years. In this issue, he writes about programmable matter [p. 32], a topic he first covered a decade ago while working on a radio program for the BBC. "In the information age, it seems inevitable that we're eventually going to start building information, and computation, into the building blocks of matter itself," says Ball.

Nancy Kress

Kress has been writing science fiction and fantasy since the 1970s, winning five Nebula Awards, two Hugo Awards, a John W. Campbell Memorial Award, and a Theodore Sturgeon Memorial Award. Her next novel, *Yesterday's Kin*, will be released in September. As in her story "Someone to Watch Over Me," in this issue [p. 72], she often writes about the unanticipated effects of technology in everyday life. "Technology is always a double-edged sword," she says. "The day that fire was discovered, arson became a possibility."

Prachi Patel

Patel is a contributing editor to *IEEE Spectrum*. In this issue, she writes about the emergence of certificate and degree programs aimed at cybersecurity specialists [p. 18]. She herself holds a master's in electrical engineering from Princeton as well as a master's in journalism from New York University. "It's interesting to see how the proliferation of new technologies—in this case, IT and networking—brings with it new jobs and education demands," she says.

Adam Voorhes

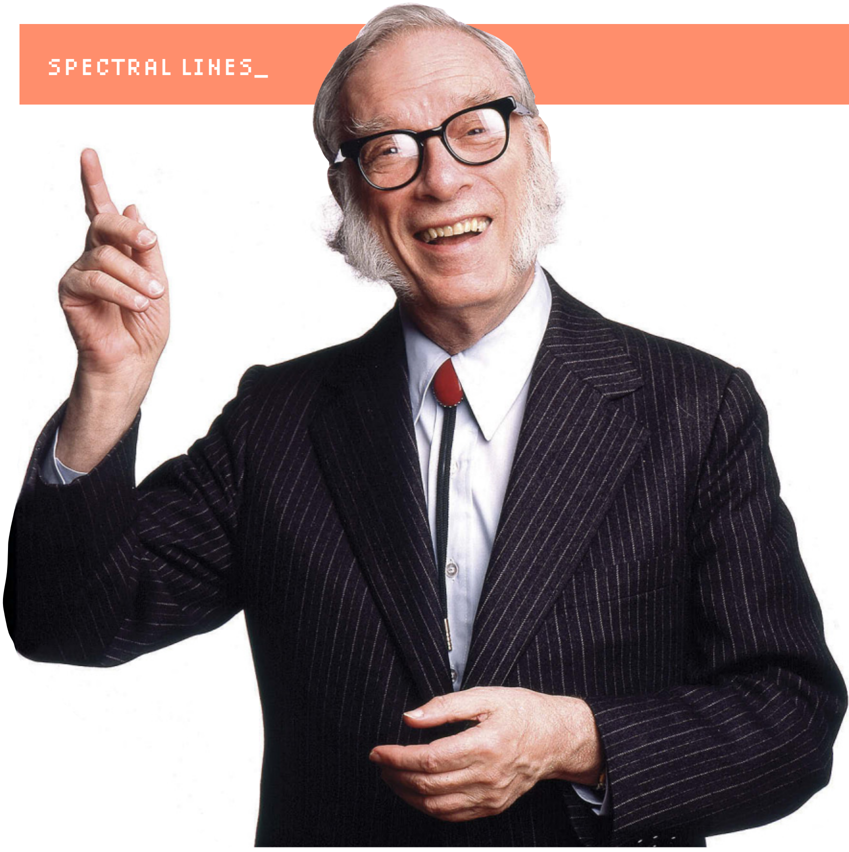
For the past five years, Voorhes has been collaborating with his wife, stylist Robin Finlay, to craft and photograph artistic marvels. It took them 8 hours to paint and strategically place 6500 tiny steel balls on the floor and chair they used in the opening photograph for "Infinitely Malleable Materials" [p. 32]. Working on four projects together for this issue posed no problems, he says. "It's really fun because we each know how the other thinks."

Ben Wiseman

"The simplest idea is always the best," says artist Wiseman. Shortly after beginning studies for a degree in illustration, he realized the curriculum wasn't for him: "It was just too nerdy to me." Opting instead for a degree in communication design allowed him the freedom to develop his own style. "I'm more of a graphic designer doing illustration," he says. In this issue, his clean, graphic approach is apparent in his image of digital doubles [p. 40] and in three other features.

06.14

PHOTO-ILLUSTRATIONS BY **Gluekit**



DEBORAH FEINGOLD/CORBIS

The Pitfalls of Prediction

If you're married, you may have concluded that marking an anniversary is an opportunity that must be handled with delicacy and imagination. And so it is for a magazine, too

THIS YEAR IS THE 50th anniversary of *IEEE Spectrum*. A half century is a milestone that cannot go uncelebrated, but how to do it? Two of the standard approaches for a magazine's commemorative issue are to take a fond look backward or a bold look forward. The *Sports Illustrated* swimsuit issue, also 50 this year, took the former tack, with a look at bikinis over the decades (it turns out that they get smaller, they get a little bit bigger, and then they get smaller again).

Forecasting is harder but more interesting. For our 50th, we wanted an inspiring and compelling view of the world of tech 25 to 50 years from now, beyond the window of straightforward prediction. We liked the idea of making inferences, at least, about a future as distant from today as we are now from the year of the magazine's founding.

IEEE SPECTRUM 1964 / 2014

We understood the risks. The Internet has made a minefield of the prediction business. It has long been accepted that any long-term forecasts you make about technology will probably be wrong and might very well be comical. That's true even if you're one of the world's smartest and most acclaimed futurists, as was Isaac Asimov [above].

It so happens that this year is also the 50th anniversary of Asimov's legendary essay outlining his vision of the world in 2014. Written on the occasion of the 1964 World's Fair in Asimov's beloved hometown of New York City, the piece is titled "Visit to the World's Fair of 2014."

And there's mistake No. 1: *There is no 2014 World's Fair.*

The anniversary of Asimov's article has prompted a flurry of fatuous articles praising his prescience. But Asimov was actually rather off the mark. Of the two or three dozen predictions in the article, only four were indisputably accurate:

1. "Robots will be neither common nor very good in 2014."
2. "By 2014, only unmanned ships will have landed on Mars."
3. "As for television, wall screens will have replaced the ordinary set."
4. "On earth...laser beams will have to be led through plastic pipes, to avoid material and atmospheric interference."

The rest of the article is a mishmash of quaint yearnings and vague warnings. He thought by now we'd have a moon colony, underwater housing, moving sidewalks (what is it with "slidewalks"?), at least one fusion power plant, jet-powered hovercraft, home appliances powered by radioisotope "batteries," and popular foodstuffs made from algae. He thought the entire area from Boston to Washington would be "a single city with a population of over 40 000 000."

Asimov would have had to live to 94 to see whether his predictions panned out, but alas, he died in 1992 at age 72.

I'm not knocking Asimov. His envisioned future wasn't so much a likely one as a desired one. If you looked at what was going on then and assumed it would continue—and had the optimism to believe that future advances would be applied aggressively to improve people's lives or lift human civilization in whatever way possible—you would end up with something like Asimov's vision.

And so we are coming clean at the outset of this issue: What we describe is a *desired* future. Like Asimov did, we started with broad areas of major technological ferment. We picked eight of them, including autonomous vehicles, wearable technology, and energy. We describe the state of the art today and likely near-term developments, and then sketch out a future in which things go well. In other words, a future in which a string of fortuitous events prevents a promising technology from being crushed by larger companies, stifled by the status quo, sidetracked by swifter or better-connected competitors, choked by regulations, undone by unforeseen problems, or shunted into oblivion by public misunderstanding, apathy, or ignorance.

A desired future may inevitably be an unlikely one. But it's enlightening, maybe even beneficial, to think about it now, and to identify the kinds of things that would have to happen for that future to come to pass.

You might ask, Why not portray the world of 25 to 50 years from now as fiction? And, indeed, we've done that, too. We are delighted to include here an original story by Nancy Kress, "Someone to Watch Over Me." It grippingly portrays how one very promising technology, implantable electronics, might be hideously misused. Kress's is one of six sci-fi stories that we commissioned especially for our anniversary, from some of the top sci-fi writers working today. The full complement, including pieces by Greg Egan, Brenda Cooper, and Geoffrey Landis, will be collected in an e-book later this year.

In publishing this issue, we have to admit to an ulterior motive. After you've all forgotten about this edition, it will live on as a kind of gift to our successors at *IEEE Spectrum* in 2064, who will be charged with coming up with material for the 100th anniversary issue. It's hard to imagine that the centennial edition of *IEEE Spectrum* will be available on printed paper. It's even harder to imagine that the centennial issue of *Sports Illustrated*'s swimsuit edition won't be available in 3-D virtual reality. But surely even in 1964 there were visionaries who believed that, at this point in the 21st century, we'd have moved beyond ink printed on pulped trees.

Had Asimov lived, he would probably have been disappointed by the fact that we have no permanent habitat on the moon, no nuclear-powered home appliances, and no significant human habitation under the sea. But that disappointment would undoubtedly dissolve in his delight at what we do have. That tally might start with

• a fast, easily accessible, planet-spanning data network;

• a pocket device that can shoot photos and video, store a huge music collection, and let its user converse or exchange text and images with another person anywhere on Earth;

• machines that can quickly and cheaply determine a person's genome; and

• space telescopes that have discovered thousands of planets outside our solar system–and that will soon be able to determine the composition of a planet's atmosphere as well.

And so, 50 years from now, staffers at *IEEE Spectrum* might very well smile indulgently at our hopes for shared autonomous cars, bioelectronic cures for disability, and a coherent strategy for space exploration. But they will surely have other things, every bit as marvelous. Probably more so.

I'll have to live to be 102 to find out if they do. To my successor I offer this advice: Make your predictions bold. And set them so far in the future that you won't live long enough to see whether they pan out.

—GLENN ZORPETTE

NEWS

20 000 KM²

AMOUNT OF FOREST LOST IN INDONESIA IN 2011

BIG DATA COMES TO THE FOREST

Activists keep watch on global forest loss with Google Earth Engine

TOP: ISTOCK PHOTO; BOTTOM: DAVID MANTEL/GETTY IMAGES

WATCHING THE WOODS: A new mapping tool uses satellite imagery to keep an eye on the world's forests from above.

When a tree falls in the forest these days, it doesn't just make a sound—it causes a computer program to generate an alert that's sent out to activists, researchers, and environmental policymakers around the planet. An online tool to map deforestation is applying big-data techniques to massive troves of satellite imagery, and in the process it is making possible a new kind of environmental activism.

The tool, Global Forest Watch, was launched by the World Resources Institute in February to provide monitoring of deforestation. Users can explore the global map to see trends since the year 2000 and can zoom in to examine forest loss at a resolution of 30 meters. The tropical zones of the map are refreshed every 16 days, frequently enough to track deforestation hot spots in places like Indonesia and Brazil. Users can also sign up for alerts, which are generated when the system detects signs of illegal logging or slash-and-burn agriculture in the tropics.

The site is powered by Google Earth Engine, which crunches image data drawn from several NASA and U.S. Geological Survey (USGS) satellites. »

Google is developing this platform to host petabytes of earth science data and to give researchers a straightforward way to use it. "They log on, access all the data, and run their own algorithms," explains David Thau, the senior developer advocate for Google Earth Engine. Thau and his colleagues work with scientists to develop useful analysis functions, and then they "get out of the way," he says, and let researchers conduct their investigations. Google Earth Engine is currently available to thousands of research partners, and the company plans a general release down the line.

Global Forest Watch is the result of a convergence of projects. The World Resources Institute's Data Lab had been working on a forest-clearing-alert system for the tropics based on data from the MODIS (Moderate Resolution Imaging Spectroradiometer), instruments that ride aboard NASA's Terra and Aqua satellites. Meanwhile, Matthew Hansen, a professor of geographical sciences at the University of Maryland, had been collaborating with Google Earth Engine on a global map of deforestation; his project used images from the Landsat satellites operated by NASA and the USGS. Both data sets are now used to create Global Forest Watch; MODIS provides better temporal resolution, while Landsat provides exemplary spatial resolution.

The researchers' algorithms create the site's dramatic map of forest loss using the satellites' visible light and infrared data. Each pixel of satellite imagery is characterized by both its color and its infrared signature, and the algorithms then compare the data for that pixel across time to detect changes. A switch from green to brown, for example, is a bad sign. Hansen pioneered this technique in his earlier research on the Congo Basin, where the ground was very often obscured by clouds. Rather than throw out the cloudy images, Hansen developed ways to create composite pictures using many days' worth of images. "We learned how to work pixel by pixel," he says.

When Landsat data became available at no charge in 2008, Hansen worked with Google Earth Engine to apply his model globally, looking at 143 billion pixels with 30-meter resolution. By tracking the pixels over months and years, the model corrects for seasonal changes to forests and can distinguish between crops and woodlands. The collaborators published their results last November, revealing a net loss of 1.5 million square kilometers of forest between 2000 and 2012. Those calculations, the researchers noted, took 1 million CPU-core hours on 10 000 computers.

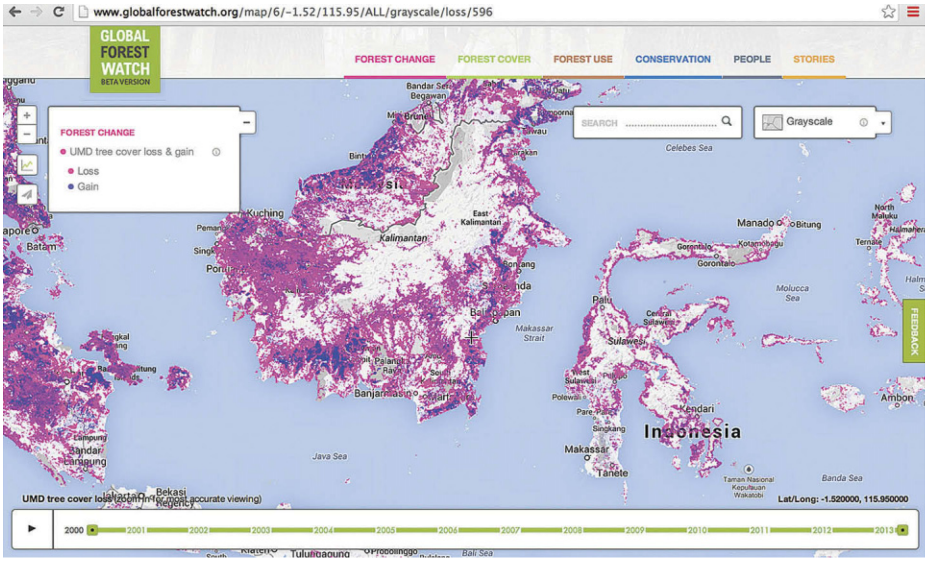
Thau says that Google Earth Engine aims to take the pain out of this big-data research. In typical cloud computing, he says, researchers have to manage the distribution of their computing tasks across the network. With Earth Engine, however, researchers simply use a programming interface to enter their queries, which get "parallelized" automatically, Thau says.

By creating the Global Forest Watch website, the World Resources Institute aims to give the public access to all that big data too. Dan Hammer, chief data scientist at the organization's Data Lab, says he expects that government agencies, businesses, researchers, and advocacy groups will use the site to get a better picture of forest management.

At the environmental action group Rainforest Action Network, agribusiness campaigner Gemma Tillack says the new tool may be particularly useful in Indonesia, where rain forests are falling to make way for palm oil plantations. Her group is asking 20 big food corporations to guarantee that the palm oil used in their products is being grown on legal, sustainable plantations. Some companies are establishing responsible palm oil procurement policies, she says, and Global Forest Watch could help them implement those policies. "They need to find out where the palm oil they're buying is coming from, and then they'll need to monitor the actions of their supply-chain partners," she says.

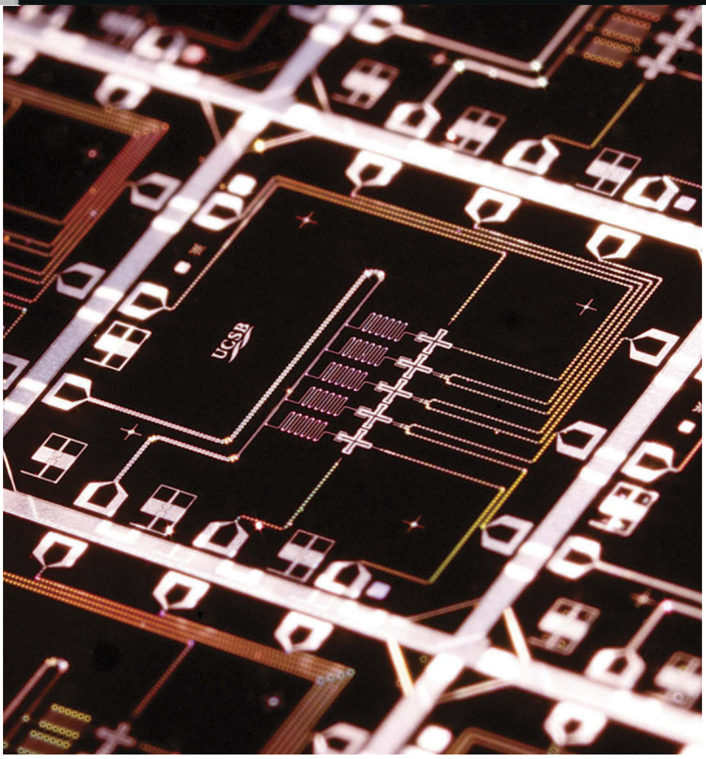
Time will tell if the site will make any difference in the seemingly inexorable advance of bulldozers, but Hammer is optimistic. "I'm consistently surprised by how much open access to data can fix things in the world," he says. Many policy decisions are delayed by arguments over conflicting information, Hammer notes, but the objective data provided by Global Forest Watch has the potential to eliminate such confusion. "That would let people get to the hard questions about what *should* be going on in the forests rather than what *is* going on," he says. —ELIZA STRICKLAND

A version of this article appeared online in April.



TROUBLE IN INDONESIA: Global Forest Watch shows deforestation in Indonesia, where land is often cleared for palm oil plantations.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®



VERY CORRECT QUBITS: A superconducting circuit could lead to practical quantum computing by allowing for error-correction algorithms.

AMAZINGLY ACCURATE QUANTUM COMPUTING

A new error-correction system could finally put these machines within reach

For quantum computing to ever fulfill its promise, it will have to deal with errors. That's been a real problem until recently, because although scientists have come up with error-correction codes, the quantum machines available couldn't use them. Now researchers have finally created a small quantum-computing array that for the first time performs with enough accuracy to allow for error correction, paving the way toward practical machines that could outperform ordinary computers.

Today's classical computers perform calculations using bits, which can be either 1 or 0. Quantum computers get their potentially amazing ability to make many simultaneous calculations by using quantum bits, or qubits, which can exist as both 1 and 0 at the same time. The challenge is that such systems must use error correction to preserve the fragile quantum states of qubits long enough to run calculations.

Error correction in the quantum world is much stranger than in classical computing. In classical computing you can simply make multiple copies of a bit at any stage in a calculation, and if the original goes afoul, you just use the copies to restore it. But physics doesn't allow you to copy quantum information exactly. Any attempt to do so disrupts the computation. But quantum-computing pioneer Peter Shor discovered that there's a way around this problem. The quantum information of one qubit can be spread across multiple qubits–hundreds or even thousands–that share a quantum connection called entanglement. Quantum error-correction codes take advantage of these other qubits to uncover the errors without really resorting to copying the value of the original qubit.

Most quantum error-correction schemes involve very simple classical processing but require quantum logic operations with an accuracy of more than 99.999 percent. But one method, known as surface code, can get away with a lower accuracy threshold of 99 percent by shifting much more of the scheme's complexity to the classical processing. An experimental system detailed recently in *Nature* demonstrated the first surface-code architecture to achieve that needed 99 percent accuracy.

"We made a significant advance in the fidelity that brought it to this important limit, and we did it in such a way that we know how we're going to scale up to more and more qubits," says one of the prototype's creators, John Martinis, a professor of physics at the University of California, Santa Barbara.

Martinis and his colleagues used superconducting quantum circuits that represent one of several possible hardware architectures for quantum-computing systems. The qubits themselves are Josephson junctions–two layers of superconductor separated by a thin insulating layer.

By creating an arrangement of five qubits in a line, the researchers showed that they could perform the logic operations at the heart of modern computing with an accuracy of 99.92 percent for a quantum logic gate involving one qubit and 99.4 percent for a quantum logic gate involving two qubits.

"The surface code tolerates a lot of error and doesn't ask much from the hard-

ERIK LUCERO

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

ware," says Austin Fowler, a staff scientist at UCSB who also worked on the quantum error-correction device.

The USCB team's success with using surface code on a linear array of qubits could lead to a full 2-D grid of qubits capable of making important calculations. The qubits would be arranged in a checkerboard pattern where "white squares" would hold data qubits for performing operations and "black squares" would contain measurement qubits that detect and correct errors in the neighboring data qubits. In this setup, the surface code can indirectly measure possible errors in the data qubits without disturbing their delicate quantum states.

IBM researchers have also done pioneering work in making surface-code error correction work with superconducting qubits. In research posted online to the arXiv repository last November, one IBM group demonstrated a smaller three-qubit system capable of running surface code, although that system had a lower accuracy—94 percent.

"Both our result and the one from UCSB are showing the promise for superconducting qubits, and that architectural and engineering challenges lie ahead of us and should begin to be addressed to get toward a fault-tolerant quantum computer," says Jerry Chow, a research staff member at IBM's Thomas J. Watson Research Center, in Yorktown Heights, N.Y.

Improved accuracy for superconducting qubits makes the technology a serious rival of other quantum-computer systems, such as the use of trapped ions as qubits.

Still, researchers must continue to improve accuracy rates before they can achieve highly reliable quantum computations, which may still require 1000 or even 10 000 physical qubits to encode a single logical qubit. The idea of connecting thousands of qubits without causing interference among neighboring qubits also presents a huge engineering challenge, though one that doesn't run afoul of any physics.

"The physics of coupling and control is not going to change," says Rami Barends, a postdoctoral fellow in physics at UCSB. "But what you'll have to come up with is the wiring and control done in a 2-D system without hampering the fidelity."

The next step for the UCSB team is to run simple error-correction experiments—a huge first for the quantum-computing field. Previously, researchers showed how to correct big errors that were deliberately injected into quantum-computing arrays. But the UCSB researchers want to show how to correct for natural errors that arise in the course of real quantum-computing operations. A combination of improved accuracy and rigorous error correction could eventually realize the dream of practical quantum computers.

"We have all the requirements for starting to tackle error correction for the first time," says Julian Kelly, a graduate student in physics at UCSB. "People have gone through the motions before, but there has never been a practical way of reducing errors in the system."

—JEREMY HSU

BREACHING THE BLOOD-BRAIN BARRIER

Redesigned ultrasound machines could help important drugs reach brain cells

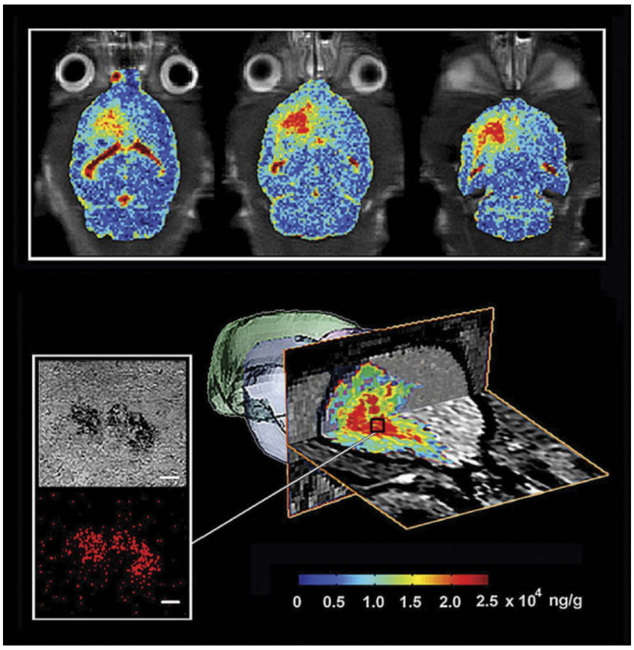
There's a barrier in your brain. Composed of very densely packed cells in the capillary walls, it restricts the passage of substances of the wrong size or chemistry from the bloodstream. Like a locked fence around your home, the blood-brain barrier prevents intruders—such as infective bacteria—from entering.

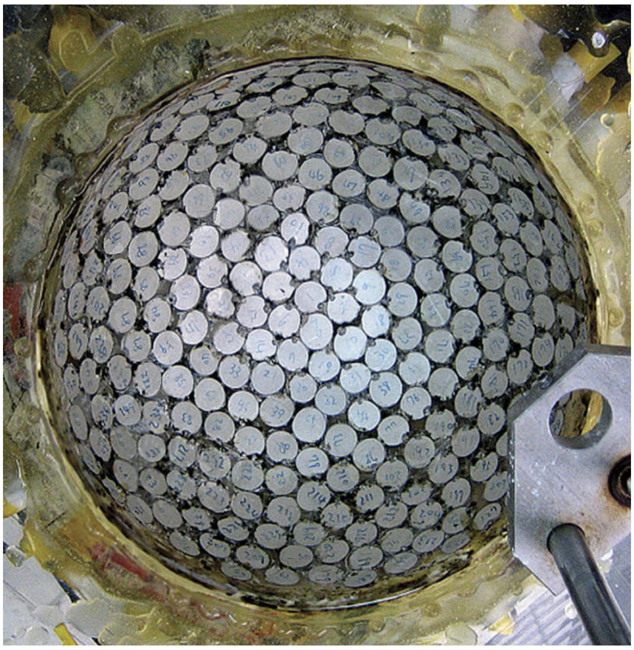
But a locked fence can also keep out rescuers in an emergency, and the blood-brain barrier keeps out potentially helpful drugs that might be able to ease the suffering of the tens of millions of people with Alzheimer's disease, Parkinson's disease, multiple sclerosis, amyotrophic lateral sclerosis, and other diseases of the central nervous system. Less than 5 percent of the roughly 7000 available drugs can get through. Basically, none of the large-molecule drugs can, severely limiting the options for new therapies.

But there's hope. Blasts of ultrasound can temporarily open the barrier in tightly focused spots of the brain that are just millimeters in diameter. And engineers at Chang Gung University, in Taiwan, have recently come up with a much improved way of delivering that energy.

The prototype device they developed is a 256-channel ultrasound phased array. According to electrical engineering professor Hao-Li Liu, his team has developed a unique circuit design involving multiple microcontrollers and power-sensing feedback circuits that enable the system to deliver two frequencies at once instead of the single frequency that biomedical researchers have been working with. By altering the phase of individual channels, the array produces millimeters-wide spots of ultrasound energy that can be electronically steered to any point in the brain.

It's been known for a while that ultrasound reversibly opens the blood-brain barrier, even if the exact workings haven't quite been nailed down. The process relies on the acoustic cavitation effect, which is the growth and collapse of microbubbles in a liquid





WINDOW IN THE BRAIN: A 256-channel ultrasound array [right] has been tested on a pig. The array could electronically steer ultrasound energy to open the blood-brain barrier and allow a substance [above, in red] to enter the brain.

HAO-LI LIU/CHANG GUNG UNIVERSITY (2)

under the influence of an ultrasonic field. (Microbubbles are injected as a contrast agent to enhance ultrasound imaging.) This effect generates an acoustic shock wave, which causes the cells in the blood vessel walls–called endothelial cells–to deform.

"Like mimosa leaves, endothelial cells contract after being shocked, thereby generating gaps. The result increases the possibility of drug delivery," Liu says, adding that other cells outside the ultrasound's focal point are undisturbed. Doctors can deliver drugs for about 1 to 2 hours, after which the gaps close.

Therapeutic ultrasound machines available on the market today destroy benign tumors of the uterus and other tissue mostly using a single frequency to generate heat at the ultrasound array's focal point.

Using two frequencies simultaneously instead can boost the power of these machines three- to fivefold, according to Liu. Greater cavitation "significantly enhances the blood-brain barrier opening," he says.

In tests using pigs–which have a similar skull thickness to that of humans–the portion of the brain the researchers were aiming for took up 10 times as much of a test dye under the influence of ultrasound as it would have otherwise. They operated the array to produce either 400 kilohertz energy, 600 kHz (an "ultraharmonic" of 400 kHz), or both at once. The dual frequency produced the best results–nearly double what the single frequency delivered without causing damage. "Of course, the performance of different drugs vary," Liu says.

Elisa Konofagou, associate professor of biomedical engineering and radiology at Columbia University, in New York City, who studies the mechanics of focused ultrasound's effects, is concerned that the Chang Gung group might not be able to improve further on the results of their system. "The frequency range seems to be on the low end," she says. "The frequencies would activate larger microbubbles–greater than 2 micrometers–when most microbubbles used are around 1 micrometer. So I'm not sure how they would enhance it."

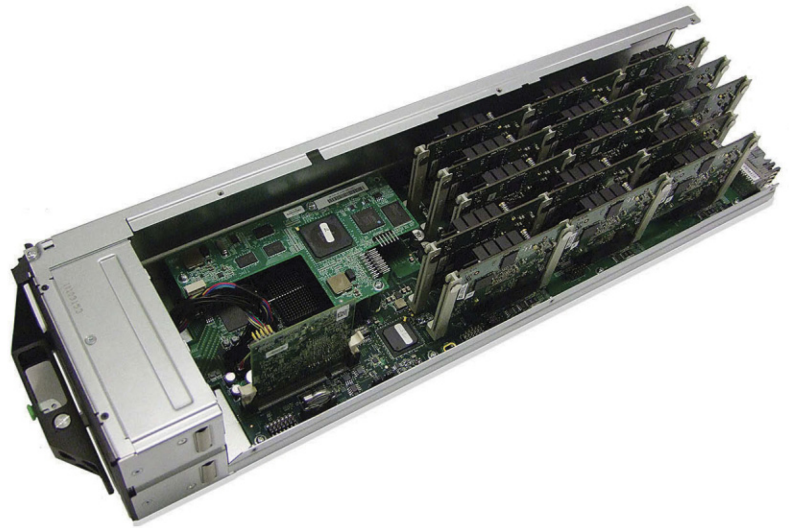
Liu counters that using multiple frequencies theoretically has a greater chance of exciting more bubbles. A bubble's resonance frequency is primarily determined by its size, so more frequencies means more bubbles of different sizes are affected.

Liu hopes that a clinical trial involving the 256-channel ultrasound system could be launched within three years after gaining the support of neurologists. What might help to achieve that goal is a solution to the problem of real-time feedback. "After focused ultrasound energy is delivered to the target position, we can't make sure if the blood-brain barrier is open. We can only have an answer postoperationally by using contrast-enhanced magnetic resonance imaging technology," Liu says. His team and others have been looking for possible solutions to the problem.

According to research led by Kullervo Hynynen, senior scientist at Sunnybrook Health Sciences Centre, in Toronto, one way to determine if the blood-brain barrier has been breached is to listen for ultraharmonic frequencies emitted by the bubbles. "This signal can be used in a feedback system to control the exposures," he says.

If researchers can prove that ultrasound can safely open a window into the brain, better drug therapies will likely step through it. –YU-TZU CHIU

NEWS



BLADES OF GLORY: Mont-Blanc's prototype contains 15 nodes made up of ARM-core processors.

EUROPE WANTS A SMARTPHONE SUPERCOMPUTER

A consortium hopes to build exaflop supercomputers from mobile CPUs

A European private-public consortium wants to make supercomputers using smartphone and tablet CPUs. And not just any supercomputers. They're shooting for the moon–aiming for exaflops (10^{18} or quintillions of floating-point operations per second), some thousandfold faster than the top of today's high-performance heap.

Supercomputing has always offered a kind of turboboosted reflection of everyday computing. In the 1970s and '80s, Cray supercomputers and their ilk were like supercharged mainframes, with just handfuls of processors that had each been designed for speed. In the 1990s and 2000s, as PCs and then laptops predominated, supercomputers became agglomerations of hundreds, thousands, and now even millions of PC and server cores. (The world's fastest supercomputer today is China's Tianhe-2, powered by 3.1 million Intel Xeon cores but capable of only about 5 percent of an exaflop.)

So in the tablet and smartphone age, it was probably only a matter of time before someone decided to make supercomputers out of the engines of present-day digital life. The thinking goes that because ARM cores are designed to run on small smartphone and tablet batteries, a supercomputer built around them could yield more speed with less power. In an age when high-performance computing, or HPC, is often constrained by heat production and electricity consumption, that could mean a more scalable machine.

Mont-Blanc, as the effort is called, began in late 2011 at the Barcelona Supercomputing Center, known for housing a supercomputer in a 19th-century cathedral. It's now got 14 partners and €22 million in backing through September 2016, and it recently unveiled a prototype blade server meant as a stepping-stone toward a full system. The prototype contains Samsung dual-core Exynos 5 CPUs–each a system-on-a-chip that includes ARM's Cortex-A15 core with a GPU. It would consume between one-fifteenth and one-thirtieth as much energy per processor as today's HPC systems, its proponents project.

Jean-François Lavignon, president of the coalition behind Mont-Blanc (European Technology Platform for High Performance Computing), says that today Intel *x*86 CPUs still offer the best performance for most supercomputer customers. And he expects that *x*86 processors combined with accelerators, such as GPUs, will continue to dominate the Top500 list of the world's fastest high-performance computers. But, he says, ARM-based computing appears to be a wise investment for the future.

ARM cores are an interesting but hardly universally agreed upon path to exascale computer architecture, says Jack Dongarra, professor of computer science at the University of Tennessee, in Knoxville. For instance, in December Japan announced its plans to build an exaflop supercomputer by 2020 using the usual processors.

"The Japanese exascale system, which will use commodity processors with an accelerator, will draw about 30 to 40 megawatts of power," he says. "One megawatt per year in the United States is about a million dollars. So just to turn it on and power it will cost you between $30 million and $40 million."

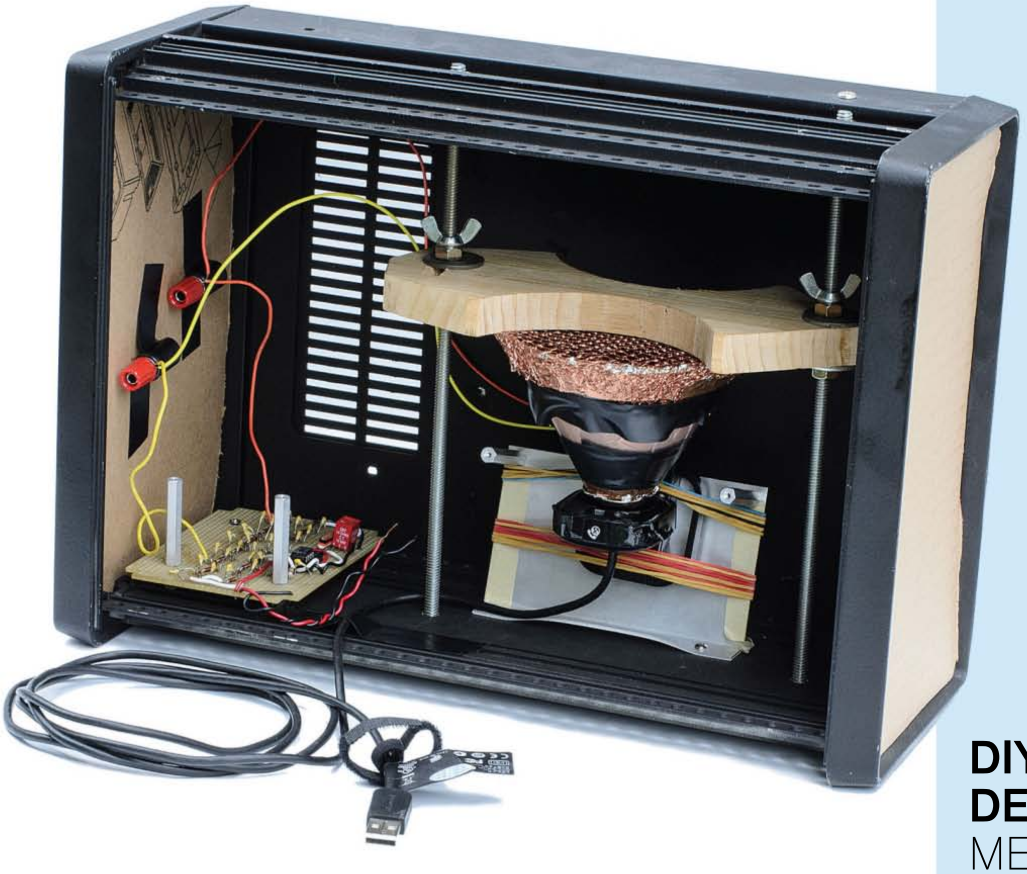
Either path that high-performance computing takes will not just have to make power consumption manageable but also reduce the challenge of writing code for what are sure to be extremely complex machines. Such code will have to run a few *billion* concurrent threads of instructions instead of the mere 12 million Tianhe-2 does today.

Addison Snell, CEO of HPC consulting firm Intersect360, says that HPC customers today, unsure of what next-generation supercomputing will look like, could be wary of investing too much in ARM-based systems out of fear that the software won't be there to support them down the line. On the other hand, he says, there's no guarantee that *x*86-based supercomputing is going to remain the dominant model for the 2020s either. ARM architecture could yet prove itself to be the secret sauce needed to make the best exascale computer. Or not. –MARK ANDERSON

MONT-BLANC

RESOURCES

THE HALF-LIFE OF RADON-222, WHICH DECAYS TO LEAD VIA POLONIUM AND BISMUTH



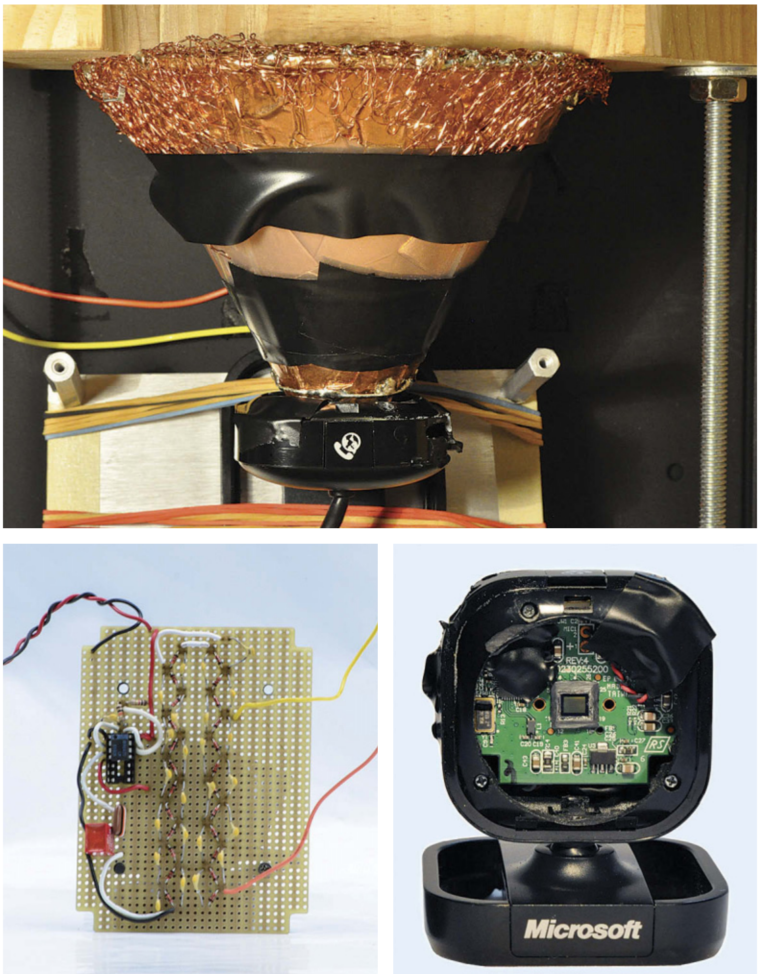
JON HOLMES

DIY RADON DETECTOR

MEASURE RADIATION WITH A CONVERTED WEBCAM

RESOURCES_HANDS ON

Over the past few years I've designed a number of radon detectors; building them is an opportunity to work on multidisciplinary projects with a social benefit. Worldwide, naturally occurring radioactive radon gas seeps from rocks and soils, where it can accumulate in buildings at hazardous levels. The World Health Organization estimates that as many as 14 percent of lung cancers are due to radon exposure. In my work at Carleton University, in Canada, I've used custom integrated circuits and specially programmed microcontrollers for my designs, but recently I wondered how I could make a detector with spare parts lying around my basement. • It turns out that you can make a cheap and effective radon detector with five basic elements: a webcam, a funnel covered with copper tape and mesh, a voltage multiplier built from some basic electrical components, a box, and a computer. • The system works because radon and some of its daughter products emit alpha particles as they decay. These alpha particles are responsible for most of the damage to human tissue that occurs when radon gas is inhaled, but they will also produce a slew of electron-hole pairs that show up as illuminated pixels should they strike the CMOS image sensor chip that's at the heart of many webcams. • As alpha particles don't travel very far through solid matter, it's necessary to cut away the protective cover over the webcam's image sensor. Starting with a spare Microsoft LifeCam VX-2000 webcam (about US $20 to $30 online), I cut away the protective cover using a Dremel tool and covered the indicator LED with electrical tape. • Putting the modified webcam into a dark, ventilated box and connecting it to a computer via a USB connection gave me a working—but very slow—radon detector. In order to make it more sensitive, I added an electrostatic concentrator to ▸



RADCAM: Copper foil and mesh applied to a funnel [top] form the electrodes for an electrostatic concentrator that boosts the count rate of the radon detector. The high voltages required are provided by a voltage multiplier [bottom left]. The detector itself is a CMOS-based webcam with its image sensor exposed [bottom right].

capture one of radon's alpha-particle-emitting daughter products.

When radon decays into polonium-218, the polonium is usually left with a positive charge, so it can be swept toward the webcam's image sensor with a suitably shaped electric field. Some copper tape (VentureTape 1626) and a powder funnel (I happened to have a Nalgene 4252-0100 powder funnel on hand) is all you need to make a two-electrode electrostatic concentrator that creates a field of the right shape. I applied the copper tape to the interior of the funnel, making sure to preserve electrical contact for both electrodes. I used a bottom electrode size and spacing of 15 millimeters. I then stretched copper mesh over the top, soldered a few spots into position, and I was done.

To get an idea of how the concentrator would behave and how strong a field I would need to generate, I modeled it using Comsol's multiphysics simulation software. For a concentrator 10 centimeters high, I estimated that an electric field strength of 50 volts per meter would suffice for collecting charged polonium-218. Although high voltages are required at the concentrator's electrodes to create this field, they aren't that hard to generate because, effectively, no current will be drawn between the electrodes.

I put together a 12-stage Cockcroft-Walton voltage multiplier driven by a bipolar 555 timer feeding a Triad Magnetics SP-4 audio transformer. The multiplier converted a 15-V supply to the 1370 V and 990 V I needed for the upper and lower concentrator electrodes, respectively. Although you should be careful dealing with voltages as high as these, the voltage multiplier supplies so little current that an accidental contact shouldn't be lethal. I also used small (1 nanofarad) capacitors to avoid a dangerous buildup of charge. But again, be careful, and proceed at your own risk. Turning on the high-voltage concentrator improved the count rate of the detector by 25 times or more. Not bad for an old funnel and copper tape!

I used Matlab software to control the webcam and also analyze the data. As the image sensor can potentially also detect less strongly interacting beta particles, I set the detection threshold, over which a pixel is considered to have been struck by an alpha, high enough to avoid noise and beta impacts. Also, when the sensor is struck by an alpha particle, an entire cluster of adjacent pixels will often register the impact, so it's necessary to identify any clusters to avoid overcounting strikes. I used an 8-nearest-neighbor algorithm to find clusters. In all, it took about 100 lines of code.

Calibrated with a Safety Siren Pro Series3 radon detector (about $130), my system counted 5.2 alpha strikes per hour in an ambient radon concentration of 159 becquerels per cubic meter. At this level of sensitivity it would take the detector about 20 hours to determine whether radon was present at levels recommended as actionable by the U.S. Environmental Protection Agency with about 10 percent accuracy.

(For the future of this detector, I am thinking of using electrostatics-modeling software to optimize the concentrator shape, electrode size, and voltage to make an even more efficient detector. It would also be interesting to rigorously calibrate the detector and observe activity dependencies on temperature, humidity, and the presence of airborne particulates.)

If you build a similar detector yourself and start reading high counts, contact a professional (or buy a calibrated detector). It might be time for radon mitigation in your own home.
—RYAN H. GRIFFIN

CLOCKWISE FROM TOP: RYAN GRIFFIN (2); JON HOLMES

PROFILE: DANNY JONES

THIS SYSTEMS ARCHITECT BUILDS THE MOST ADVANCED F-16 COMBAT SIMULATORS

DANNY JONES

BITS IN FLIGHT: With advanced graphics technologies, this simulator can faithfully mimic the challenges an F-16 pilot can face during combat missions.

Flying combat missions in a jet fighter requires reflexes that can respond to challenging terrain, shifting mission objectives, and hostile forces. Danny Jones is helping U.S. Air Force pilots develop those reflexes by building perhaps the most advanced military flight simulator in the world.

Jones is the systems architect for the F-16 Mission Training Center (MTC) simulator built by L-3 Link Simulation & Training, headquartered in Arlington, Texas. The MTC was first employed by Nellis Air Force Base, in Las Vegas, in February 2012, and it has since been rolled out to several more bases in the United States and overseas. Each MTC can accommodate four pilots simultaneously, and all of the MTCs can connect with each other for large-scale networked virtual training exercises.

As the United States increasingly fights in cities and towns, "the idea is to aid the pilot in immersion in a dense urban environment and provide a more realistic view of what they would see in an actual flight," says Jones.

Simulator training enables more flying practice and per-session combat training exercises at considerable savings. It costs about 97 percent less per hour to operate an MTC than to actually fly four F-16s. Not least are the savings on wear and tear: Each MTC is expected to last 20 years, but the aircraft's service life is limited to 12 000 flight hours.

The MTC system advances the state of the art through sharper visuals, more realistic city landscapes, and artificial intelligence–controlled vehicles and pedestrians that react to the aircraft and each other. Each MTC is powered by a combined total of 440 servers. The simulators re-create the F-16 cockpit, tactical controls, vibrations, and visuals on a 360-degree, 18-facet domed display.

The system also simulates views coming through infrared and low light optical sensors, as well as night-vision goggles. The latter required the particularly complicated task of replicating their imperfections, such as depth perception loss or light blindness when firing weapons. "The challenge of simulating night-vision goggles was duplicating the same miscues and effects they would have in the aircraft," says Jones. "That way pilots can learn corrective habits."

Jones earned a bachelor's in mechanical engineering from Mississippi State University in 1984, and he spent his career working his way up in flight simulation systems at companies like Link, Raytheon, Hughes, and now L-3.

"Mechanical engineering gave me a mind-set and process for architecting components and building them over time," he says. "But I liked the flexibility of working in software and being able to create something much faster than working with actual hardware." That flexibility has come in handy when adjusting to increasingly rapid improvements in video and graphics hardware.

"The whole simulation visual capacity technology out there today is moving at an extremely rapid pace, driven to a large extent by the gaming industry," says Dan Kelly, L-3's vice president of Air Force programs. "Fifteen years ago, simulation used to be done with custom products; today it's almost all commercial off-the-shelf."

Currently, the MTC synchronizes the output of more than 100 graphics cards into a seamless scene across the pilot's 360-degree field of view, says Jones. "But instead of flat panels, we're now working on a more streamlined system using curved LCDs or LED displays to create a domelike environment that requires fewer cards, thereby reducing its computational footprint."

The system feels so lifelike, Jones hesitates when asked if he, too, is a pilot. "I'm confident enough to think that I am," he says, laughing. "I've spent enough hours in the simulator that I claim I can fly." —SUSAN KARLIN

PHOTO: SWISS FEDERAL OFFICE OF TOPOGRAPHY

PHOTO-ILLUSTRATION BY Gluekit

DEFENSE AGAINST THE DARK ARTS (OF CYBERSPACE)

UNIVERSITIES ARE OFFERING GRADUATE DEGREES IN CYBERSECURITY

In an increasingly networked world, security attacks have become not just more frequent and sophisticated but also more financially damaging. The silver lining is the growing need for cybersecurity experts. Information security analyst jobs are expected to grow by 37 percent by 2022, according to the U.S. Bureau of Labor Statistics. "Every time there's a new breach anywhere, a light goes on in some C-suite office and it opens up hiring," says Ernest McDuffie, who leads the National Initiative for Cybersecurity Education (NICE) at the U.S. National Institute of Standards and Technology.

Consequently, more and more institutions now offer specialized master's degrees in cybersecurity. Big names like IBM and Intel are collaborating with schools to keep security curricula up to date. "Today many companies are educating their workforce on their own," says Marisa Viveros, vice president of IBM's Cybersecurity Innovation Program. "But we also need universities to take that in a formal, programmatic manner and teach principles and fundamentals." The NICE initiative, meanwhile, hopes to improve awareness and education and lists over 180 higher-education facilities as cybersecurity centers of academic excellence.

Previously, a computer science degree, on-the-job training, or even self-taught hacking skills had been enough to qualify someone for a security position. But cybersecurity has expanded enough in depth and scope in the past decade to warrant its own degree, says Gene Spafford, executive director of Purdue University's Center for Education and Research in Information Assurance and Safety. "Ten years ago, somebody involved in security would be doing data acquisition and response. Now. . .somebody involved in security has to be doing risk analysis and threat evaluation. They need to know law enforcement and forensics, planning and policy."

Purdue's cybersecurity program produces more graduates every year, and they steadily find employment, Spafford says. Master's students get five-plus offers, while Ph.D.s get two to three apiece. Spafford feels this level of demand will hold up, at least for now: "One recent report says that the average starting salary for hires in the D.C. area is around US $116 000 a year. If there was an oversupply, that would not be the case."

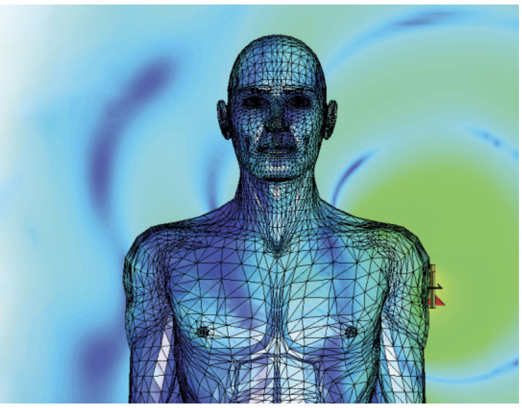
Cybersecurity master's students take basic computer science courses, but two-thirds of their curriculum covers specialized areas such as network security, cryptography, data forensics, and policy, says Wenke Lee, director of the Georgia Tech Information Security Center. Hands-on lab courses and real-world projects defined by outside organizations or companies round out the education. This in-depth training is crucial to becoming a security specialist, says Lee.

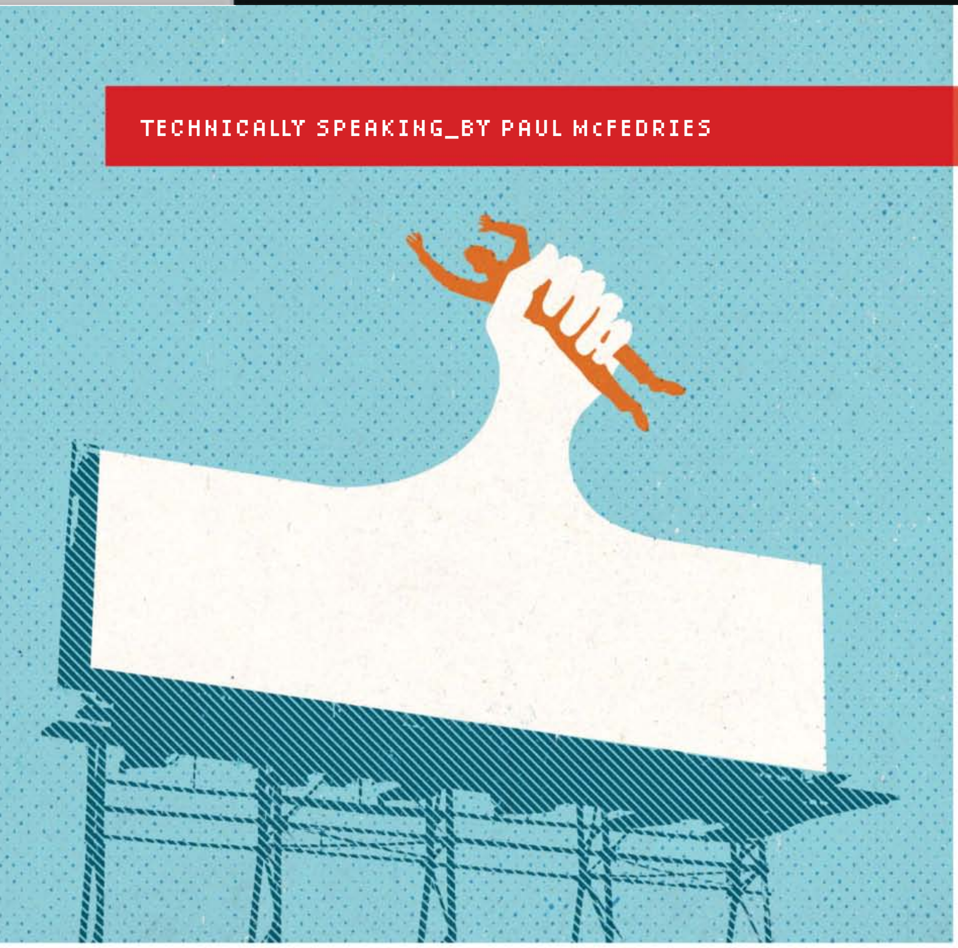
Outside the United States, IBM has partnered with more than 200 universities around the world to equip students with security skills. Registered faculty at these institutes can access an IBM-developed curriculum and software portfolio online. Viveros says she had been astonished to find that before the IBM program, some schools in countries such as Poland and Mexico had never heard of the topic.

Indeed, the biggest challenge academic programs face might be getting enough interest. A survey by defense company Raytheon found that less than one-quarter of young adults in the United States believed a cybersecurity career is interesting at all.

One solution is to simply get the career on students' radar, says Sukumaran Nair, chair of the computer science and engineering department at Southern Methodist University, in Dallas. In the Raytheon survey, 82 percent of respondents say that no high school teacher or guidance counselor ever mentioned the idea of a career in cybersecurity. "Once it's clear to fresh grads from high school that this area will guarantee jobs, it's very likely that they'll choose this line of education," Nair says. "Universities are well prepared to train them." —**PRACHI PATEL**

ILLUSTRATION BY Jesse Lefkowitz





STOP, ATTENTION THIEF!

Unwanted interruption-based advertising [pilfers] time and focus I could have reserved for dearer claims on my bandwidth, such as my family and friends. Simply put: Attention theft is a crime. —Tom Hayes

WRITING MORE THAN a hundred years ago, the German sociologist Georg Simmel observed, "The psychological basis of the metropolitan type of individuality consists in the intensification of nervous stimulation which results from the swift and uninterrupted change of outer and inner stimuli." Which is a long way of saying that living in a city requires a great deal of our attention. • And just a year ago, the screenwriter Bill Oakley quipped, "Describing today to someone from 1953: Every 6 seconds all your friends send you a telegram and a brand-new *Life* magazine is thrown at you." That is to say, living in a networked world requires a great deal of our attention. • What happens when we combine these two ideas? When the city and the network come together, we have the topics of my previous two columns: urban computing and the smart city. The upsides of these new paradigms are significant, and they include improved efficiency, increased civic engagement, and enhanced awareness of one's surroundings. But there are substantial downsides as well, including constant connectivity, the potential for surveillance, and a tendency to see the interface instead of the city. • Perhaps the biggest problem with living a networked, urban life is the seemingly endless supply of distractions. Our default mode of perceiving the world is what psychologists call *bottom-up attention*, where we notice whatever is most salient in our surroundings. "Most salient" used to mean "most dangerous" or "most edible," but now it usually means "most distracting." Hucksters, marketers, and social media gurus know that we're suckers for arresting images, that we can't resist a smartphone's ping, and that we suffer from what Aldous Huxley called "man's almost infinite appetite for distractions."

So now, it's not enough to rely on nature or social ties to get our attention. Now we must deal with **engineered distraction**, stimuli designed so that we can't help but notice them. It's one thing to have **FOMO** (fear of missing out) engender a **compulsive connectivity** that has us constantly staring into our **glowing rectangles** and **infinity machines**. But when the distraction engineers build attention-grabbing interfaces into a city, and when those interfaces are the only way to interact with a resource and so are a kind of **coercive connectivity**, then we're dealing with nothing less than **attention theft**.

The metaphor of theft is apt. As many have pointed out, we're living in an **attention economy**, and when we focus on something we say we are *paying attention*. If land is said to be increasingly valuable because nobody's making any more of it, then attention is increasingly precious because there's only a finite amount of it to go around. In his landmark work, *Principles of Psychology* (1890), William James wrote, "My experience is what I agree to attend to." So what kind of experience can we expect when our walks and rides through the city are inundated with **data smog**?

And that smog will soon know our names. Marketers are already using **directed sound** to aim audio advertisements at individuals, and it won't be long before facial recognition is added (thanks, Facebook!), so the once-distant future of *Minority Report*-style personalized advertisements will soon be coming to a sidewalk near you.

So, yes, we can turn off our phones, but that won't stop the **information pollution**. Wearable-computing pioneer Steve Mann once invented glasses that could hide noxious urban landscape images with more pleasing scenes projected onto the lens, but are the extra visuals of augmented reality really the answer to **visual overload**? Yes, we can hide or secure our valuables to guard against theft, but how do we protect our attention from being hijacked against our will? The answer, I'm afraid, will have to wait until my next column. ■

ILLUSTRATION BY Dan Page

MULTIPHYSICS SIMULATION

Sponsored by COMSOL

Special Advertising Section to:

IEEE SPECTRUM

JUNE 2014

SIEMENS OPTIMIZES POWER TRANSFORMERS

PAGE 6

INNOVATIVE ELECTRONICS COOLING DESIGNS FROM BELL LABS

PAGE 19

SIMULATION ENSURES DOUBLE BEAM THROUGHPUT AT FERMILAB

PAGE 12

INNOVATIVE DESIGN BEGINS WITH SIMULATION SOFTWARE

By **JAMES A. VICK, SENIOR DIRECTOR, IEEE MEDIA; PUBLISHER, IEEE SPECTRUM**

TODAY'S DESIGN CHALLENGES can't be addressed without simulation software. Take the development of smart grid technologies, for example. Trying to solve the enormous engineering problems that smart grids present through the use of standards, ad hoc design methodologies, or physical testing alone would be prohibitively inefficient and expensive. But accurate simulation software, combined with solid engineering skills, can make cost-effective solutions for challenges like smart grid design realizable.

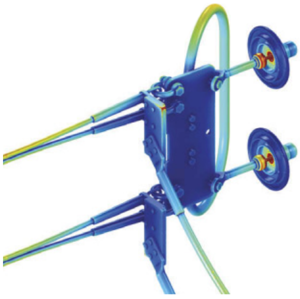
This year's *Multiphysics Simulation*, sponsored by COMSOL, spotlights engineering thought leaders and their work. The diverse application areas discussed here include optical antennas, power electronics, transformers, high-tech cables, particle accelerators, energy-efficient telecom devices, appliances, semiconductor manufacturing, and smart materials.

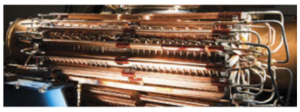
One common theme, however, runs through many of the stories that follow: To achieve energy efficiency, you need flexible, powerful thermal management. For example, engineers at Siemens are simulating the mechanical structure of a power transformer to accurately locate and minimize the effect of hotspots caused by inductive heating. At Bell Labs, engineers are designing new microthermoelectric coolers to precisely control laser wavelength in high-speed optical communication systems. Similarly, Whirlpool engineers and designers are establishing simulation protocols to predict the thermal efficiency of heat transfer in household ovens.

The talented engineers and researchers featured in these stories use multiphysics simulation tools to achieve remarkable product design results. We hope you enjoy them. To access the electronic version of *Multiphysics Simulation*, visit www.comsol.com/resources. ◎

Email: jv.ieeemedia@ieee.org

CONTENTS





ON THE COVER: An RF cavity with ferrite tuners from the Booster synchrotron at Fermi National Accelerator Laboratory. See Fig. 6 from the full article starting on pg. 12 for more details about the simulation. Photo is by Reidar Hahn and COMSOL simulations by Mohamed Hassan, both of Fermilab.

+ ONLINE: www.comsol.com/products

ENHANCING TRANSMISSION LINE PERFORMANCE: USING SIMULATION TO OPTIMIZE DESIGN

The design of high-voltage transmission lines involves optimization under a complex series of economic, electrical, mechanical, and environmental constraints. Using simulation, POWER Engineers, Inc. analyzed transmission line corona performance prior to device manufacturing and high-voltage testing, saving both time and money.

By **ALEXANDRA FOLEY**

LEVERAGING HIGHLY accurate simulation technology and knowledge gained from decades of analyzing in-service equipment, today's engineers are able to investigate, model, and neutralize subtle effects that were impossible to assess without expensive and rigorous testing even just a few years ago. One area in which simulation is successfully being applied is in the analysis of the adverse effects of corona discharge in bulk power transmission lines and their associated equipment.

While analyses of this sort are usually conducted through testing in high-voltage labs or by evaluating in-service equipment, POWER Engineers, Inc. (POWER), a global consulting engineering firm, found that finite element simulation software was an effective tool for analyzing the corona performance of transmission lines. As an example, under contract to a Midwestern utility company, POWER performed detailed studies of corona performance for special 345-kilovolt transmission line equipment proposed to mitigate mechanical stress due to wind and ice loads. These studies provided a better understanding of the device's electrical performance prior to high-voltage testing in the laboratory.

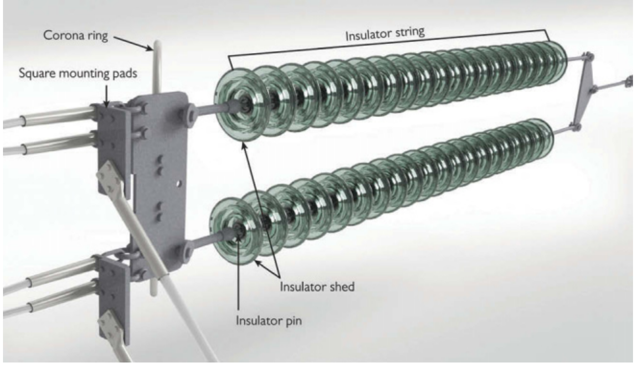


FIGURE 1: Top: A dead-end structure. Bottom: CAD representation of the dead-end insulator assembly.

IMAGES COURTESY OF DANNY FREDERICK AND CHARLIE KOENIG, POWER ENGINEERS, INC.

» CALCULATING ELECTRIC FIELDS FOR COMPLEX GEOMETRIES

TRANSMISSION STRUCTURES designed to support significant lateral forces from conductor tension are called dead-end structures. Insulator assemblies mounted on these structures provide an electrically isolated connection between the structure and the energized conductor (see Figure 1). Electric fields near the surface of these high-voltage conductors and dead-end assemblies can ionize the surrounding air molecules, resulting in corona discharge. The effects of this phenomenon include energy losses, electromagnetic (AM radio) interference, audible noise, visible light, and possible erosion of materials.

"If you've ever stood near a transmission line, you've probably heard the buzzing noise it makes," says Jon Leman, Senior Project Engineer at POWER. "Above a certain voltage, the

> *"The COMSOL software combines the tools necessary for us to provide our customers with an accurate analysis of how the proposed transmission hardware will perform."*
>
> **—JON LEMAN, SENIOR PROJECT ENGINEER AT POWER**

electric field ionizes air molecules and creates corona discharge. Usually that's what causes the noise you hear. Minimizing this noise and other negative effects requires reducing corona discharge." A certain level of corona activity and associated effects are tolerable for transmission line conductors, but attachment hardware is typically supposed to be free of noticeable corona activity. Leman used COMSOL Multiphysics® to determine the electric field strength near the surface of the energized hardware and to estimate the probability of corona discharge at locations with high electric fields.

"In order to set up a lean simulation, we modeled the insulator assembly for one of the three transmission line phases and only included the first unit of the insulator string," says Leman. POWER then used a 2-D axisymmetric model of the complete

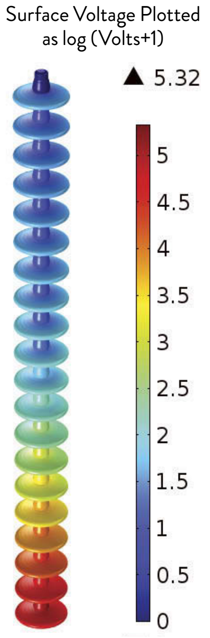


FIGURE 2: A 2-D axisymmetric model showing the electric potential distribution along the insulator string.

insulator string to determine the floating potential on the last insulator unit's cap (see Figure 2). Knowing this boundary voltage allowed POWER to build a reasonably accurate 3-D model without having to include the repetitive geometric complexity and computational burden of the whole insulator string.

» PREDICTING DEVICE CORONA PERFORMANCE

CORONA DISCHARGE IS a complex physical phenomenon affected by a combination of electric field strength, device geometry, atmospheric conditions, and the surface condition of the conductor. Leman performed custom postprocessing of the electric field results by entering empirical, space-dependent equations into COMSOL to estimate the net number of air ionizations near regions with high electric fields. This allowed him to estimate the probability of corona activity. Results showed that there were two areas with electric fields strong enough to result in corona discharge: The energized pins of the insulator units and the corner of the upper square mounting pads (shown as red areas in Figure 3).

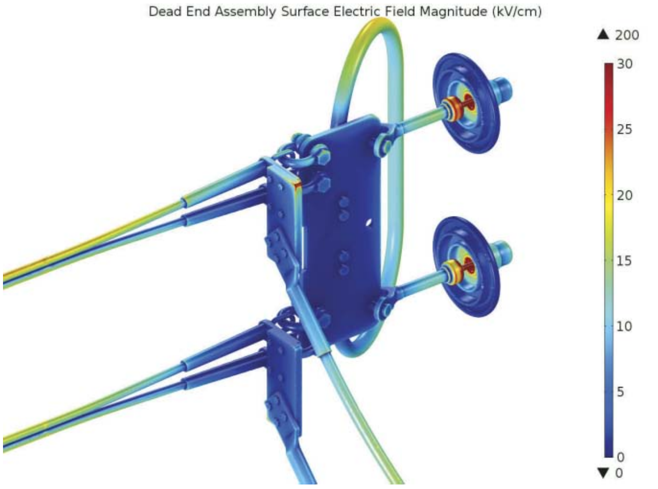


FIGURE 3: Electric field strength at the surface of the dead-end insulator assembly. Areas with high electrical fields occur at the pins of the insulator units and at the square mounting pads.

"Our results demonstrated that the outside corners of the square mounting pads are likely susceptible to corona discharge, but only marginally so," explains Leman. "The insulator pins, however, may experience significant corona discharge." Detailed views of the electric fields present at the insulator pins are shown in Figure 4.

In addition to audible noise and radio interference, severe corona discharge can deteriorate the insulator unit over time, possibly resulting in loss of strength and insulating capability. "Now that we have identified where the issues are likely to occur on the hardware, it will provide an opportunity to modify the design prior to testing," says Leman. Rob Schaerer, a project engineer at POWER who also participated in the project, coordinates procedures and witnesses high-voltage corona testing for clients. He says, "Laboratory testing is an important part of new hardware design, but there are costs that can be saved by up-front analysis, particularly if retesting is required. Scheduling time in high-voltage labs can be difficult on short notice, so by having a reasonably vetted design prior to testing,

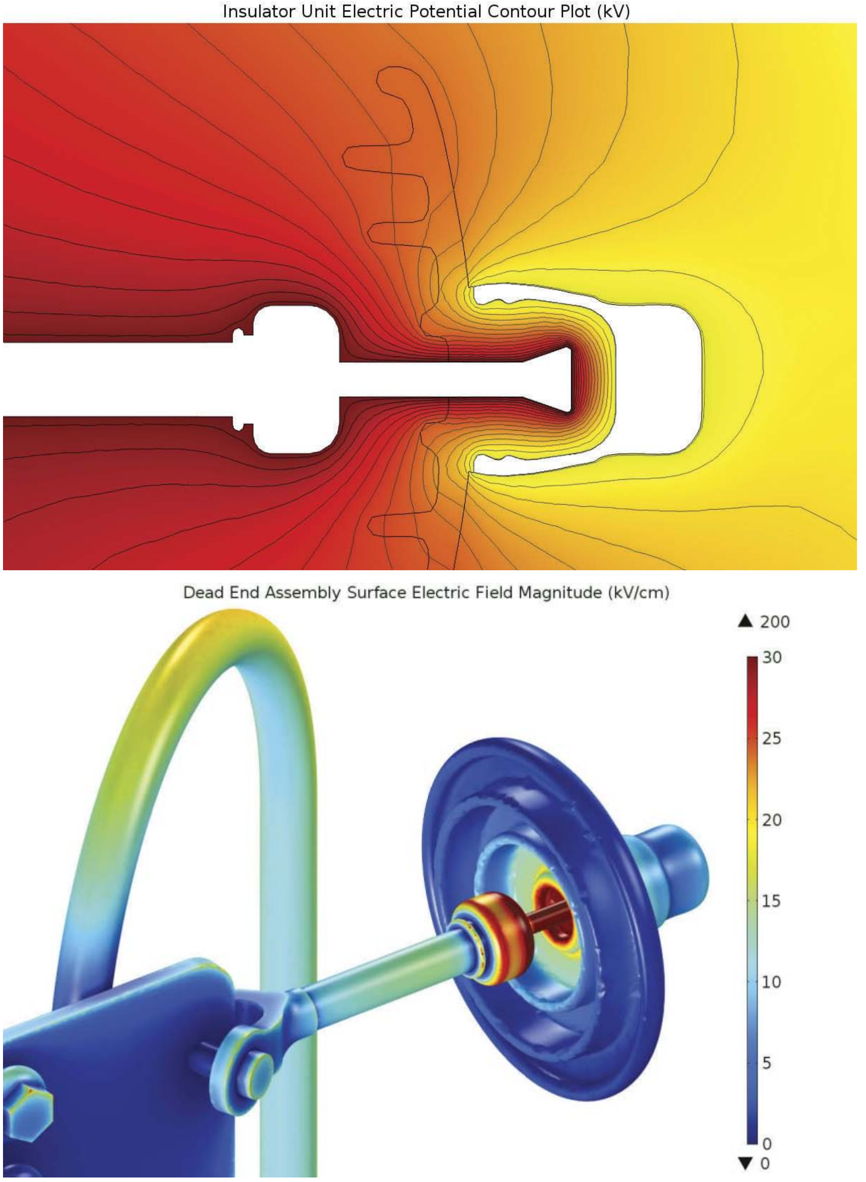


FIGURE 4: Top: Electric potential cross-section of the air surrounding the insulator pin. Bottom: Electric field results for the insulator pin.

Jon Leman, Senior Project Engineer at POWER

Rob Schaerer, project engineer at POWER

Charlie Koenig, Visualization/ Animation Specialist at POWER

a project is less likely to be impacted by a design that's found to be insufficient in the first round of testing."

» ACCURATE SIMULATIONS DRIVE REAL-WORLD RESULTS

SIMULATION CAN BE used to provide information about how a device will perform prior to its construction. When combined with results from empirical testing, engineers can arrive at a reasonable prediction of how a new device design will perform. "I have great respect for the engineers who built the electric grid without the use of modern computing. It's important that we combine that ingenuity with the use of advanced tools to efficiently design tomorrow's grid," says Leman. "The COMSOL software combines the tools necessary for us to provide our customers with an accurate analysis of how the proposed transmission hardware will perform, allowing opportunities to reduce design iterations that would otherwise take place after high-voltage testing." Examples such as this show how simulation can change the process by which devices are designed in order to reduce costs and more quickly optimize solutions. ◎

SIMULATION ENABLES THE NEXT GENERATION OF POWER TRANSFORMERS AND SHUNT REACTORS

Transformers are the workhorses of the electrical grid, and now they are getting assistance from computer modeling in order to meet today's power demands.

By **DEXTER JOHNSON**

DESIGNERS AT SIEMENS BRAZIL, located in Jundiaí, São Paulo, are employing simulation to guarantee the safety of power transformer and shunt reactor operation. By performing these simulations in addition to using their internal tools, members of the design team at the company are now better able to control overheating despite the increasing power demands placed on this equipment.

Shunt reactors are used to absorb reactive power and increase the energy efficiency of transmission systems (see Figure 1). Power transformers are designed to efficiently transfer power from one voltage to another. Both devices are used in all stages of the electrical grid, from power generation to distribution to end users. The increasing demand for more power from constantly growing cities is translating into a need for larger devices. But sometimes conditions limit their size: Transportation and space to place the devices at the customer's plant are some examples of these limitations.

The need to produce more power without increasing the device size adds additional load and increases thermal losses, eventually leading to higher temperatures. While methods for the design of active parts (the cores and windings) of these devices are well-established, the design of their inactive components (structural parts) is still not straightforward and requires further investigation. If the equipment is not carefully designed, there is a risk of overheating, potentially leading to the degradation of the material properties of the transformer's insulating oil.

FIGURE 1: Shunt reactor. In the original design of the oil circuit the radiator is connected to the tank by pipes enclosed in rectangular boxes welded to the exterior of the reactor.

» OVERCOMING INDUCTIVE HEATING ISSUES

SIEMENS HAS EMPLOYED COMSOL® simulation software to address these design constraints and control the inductive heating of metal parts. Induction heating is the phenomenon of heating a conductive body subjected to a varying electromagnetic field, where eddy currents lead to the Joule heating of the material due to electrical resistance.

The modeling of inductive heating has helped designers at Siemens avoid "hotspots"—small regions with high induced current density and, consequently, high temperatures. With the geometric and material complexity of these transformers, it is very difficult to avoid these hotspots completely. The oil in immersed transformers is a powerful electrical insulator and also works as a coolant fluid. However, these hotspots can overheat the oil and bubbles of gas can be generated. These bubbles have a smaller dielectric strength than the insulating oil and may cause an electrical discharge in the oil, potentially damaging the transformer.

"With COMSOL, we can simulate this behavior and propose changes to transformer design to reduce inductive heating of structural parts," says Luiz Jovelli, Senior Product Developer at Siemens.

In their inductive heating work, Siemens used COMSOL Multiphysics® and the AC/DC Module. The first change that was made as a result of the simulation was to alter the design of the metal structure. For example, by changing the original clamping frame structure of the shunt reactor (see Figure 2, top), the design team was able to reduce induction heating and improve cooling with better oil circulation through that region. As a result, the temperatures of the hottest points were reduced by about 40°C. This change eliminated the need for installing copper shielding over the clamping frame, thus saving material costs (see Figure 2, bottom, and Figure 3).

Because of the simulation work Jovelli and his colleagues have done with COMSOL, they have been able to suggest several improvements to the design of these devices. "Sometimes the cooling accessories of the equipment may be over dimensioned to fit some hotspots in the whole design," says Jovelli. "With COMSOL, we're able to control these spots." Jovelli noted that even a slight change can solve the problem and lead to a reduction in the costs associated with cooling accessories.

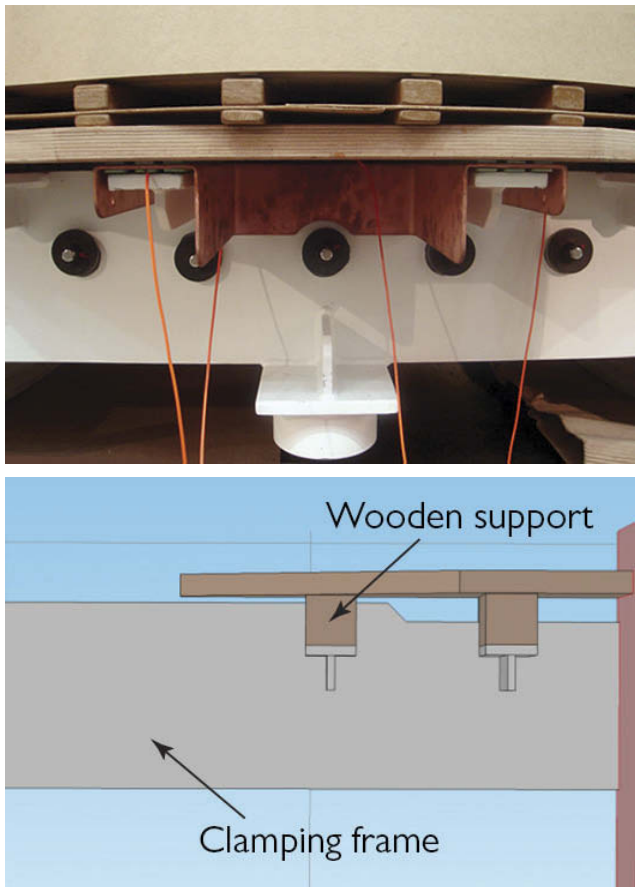


FIGURE 2: Top: Original clamping frame design with copper shielding. Bottom: Optimized clamping frame design using less materials.

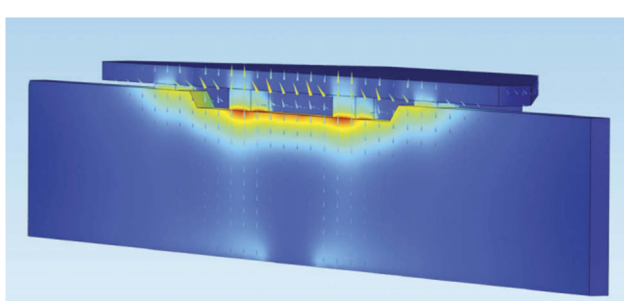


FIGURE 3: Optimized design of the clamping frame (back view). Temperature (surface plot) and oil flow fields (arrows) are shown.

"COMSOL is a powerful modeling and simulation software," says Jovelli. "We can improve the accuracy of our calculations by performing numerical experiments with it. It is also an ally against failure. Design checks can be quickly done to guarantee equipment quality for the entire service life."

» COOLING THE CORE MORE EFFICIENTLY

FROM A THERMAL point of view, a shunt reactor's core has higher heat loss relative to its winding than power transformers, i.e., the ratio of core loss to winding loss in a reactor is higher than in a transformer, and overheating may occur. Therefore, the design must guarantee the efficient cooling of the reactor's core (see Figure 4).

In this case, Siemens simulated the oil circulation and heat transfer in a shunt reactor to understand the oil's behavior and propose an optimized design. A small change in design improved the core cooling, is cleaner than previous designs, reduced man-hours of maintenance, as well as saved material.

Another change that was made involved the piping welded in the tank of the reactor (see Figure 1). Changing this design to the one shown in Figure 5 has reduced material and manufacturing costs and improved oil distribution at the bottom of the reactor tank.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page
Qmags THE WORLD'S NEWSSTAND®

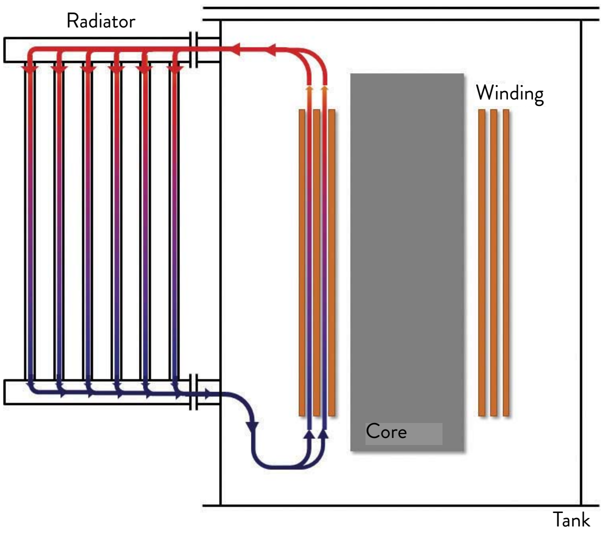


FIGURE 4: Schematic of the new oil circuit design used in shunt reactors and power transformers.

» *COUPLING 1-D, 2-D, AND 3-D MODELS INTO ONE FULL OIL CIRCUIT SIMULATION*

JOVELLI AND HIS colleagues are also modeling the 3-D thermohydraulic behavior of free convection of oil inside a power transformer (see Figure 4). It is typically quite computationally demanding to perform computational fluid dynamics (CFD) simulations of transformers by representing all parts in 3-D.

COMSOL offers the ability to take a pipe or channel of a transformer and simulate it efficiently in 1-D. A particular strength of the software is that the pipe and channel models seamlessly combine with larger entities modeled in 2-D and 3-D.

"In order to perform a realistic 3-D CFD simulation of an entire transformer oil circuit with this amount of detail, a large amount of computer resources are required," explains Jovelli. "Sometimes simplifications have to be made, and, depending on the objective, you don't get reliable results. With COMSOL Multiphysics, we can easily couple 1-D, 2-D, 2-D axisymmetric, and 3-D models for any physics and perform this simulation on a single workstation with desired reliability."

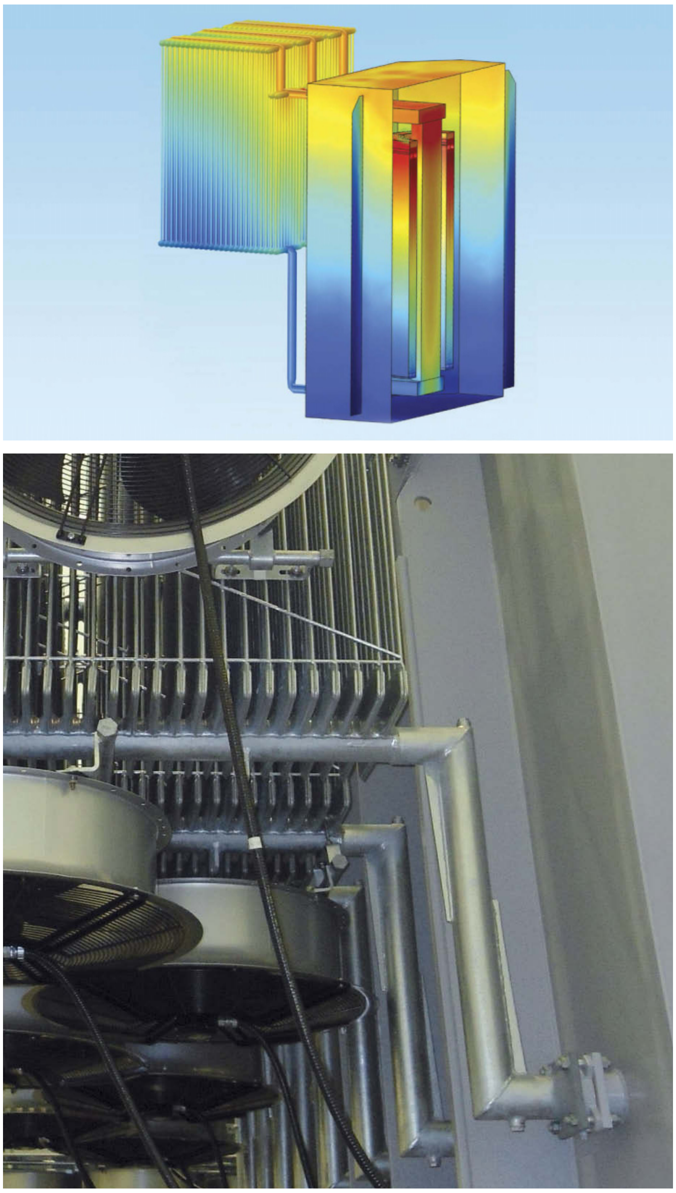


FIGURE 5: Top: The thermo–fluid dynamics simulation of the new design. Bottom: New collecting pipes design. In the new design, the pipes have been removed from their previous position circling exterior of the reactor. Instead, the pipes travel directly from the cooling fan and into the reactor itself.

> *By using COMSOL and its multiphysics coupling capabilities, we're the first Siemens Transformer unit in the world to make a real 3-D model of this equipment."*
>
> —**LUIZ JOVELLI, SENIOR PRODUCT DEVELOPER, AND GLAUCO CANGANE, R&D MANAGER AT SIEMENS**

Using the unique ability of COMSOL to map data from edges (1-D) to surfaces (2-D and 2-D axisymmetric) and volumes (3-D), Jovelli was able to model the windings of transformers using a 2-D axisymmetric model. Additionally, the tank and inlet and outlet pipes were modeled in 3-D, and the heat exchangers were modeled using 1-D elements. The silicon steel core is also a heat source and was modeled in 3-D. Since thin sheets of silicon steel make up the core of the transformer, their anisotropic thermal properties have also been taken into account.

» THE MULTIPHYSICS APPROACH DELIVERS REALISTIC RESULTS

FOR JOVELLI AND his colleagues, COMSOL makes it possible to perform more realistic simulations of equipment due to its multiphysics capabilities.

"The ability to couple physics allows us to accurately model real-world physics in a manner that is computationally efficient," say Jovelli and Glauco Cangane, R&D Manager at Siemens. "By using COMSOL and its multiphysics coupling capabilities, we're the first Siemens Transformer unit in the world to make a real 3-D model of this equipment. Maybe we're even the first transformer manufacturer to do it." ◎

MODELING TIPS: INDUCTION HEATING

BY VALERIO MARRA

THE ABILITY TO create multiphysics models is one of the more powerful capabilities of COMSOL Multiphysics®. Several predefined couplings are available where the settings and physics interfaces required for a chosen multiphysics effect are already included in the software. The user interested in modeling induction heating can select the Induction Heating multiphysics interface (Figure 1) that automatically adds a Magnetic Fields interface and a Heat Transfer in Solids interface. In addition, the necessary multiphysics couplings are defined where electromagnetic power dissipation is added as a heat source (Figure 2, Added physics section) and the electromagnetic material properties depend on the temperature. The next step is to select study types such as Stationary, Time Dependent, Frequency Domain, or a combination. Combined frequency-domain modeling for the Magnetic Fields interface and stationary modeling for the Heat Transfer in Solids interface is referred to as a Frequency-Stationary study and, similarly, Frequency-Transient modeling is also available (Figure 2, Added study section). The Magnetic Fields interface is used to compute magnetic field and induced current distributions in and around coils, conductors, and magnets. The Heat Transfer interfaces provide features for modeling phenomena such as phase change and heat transfer by conduction, convection, and radiation.

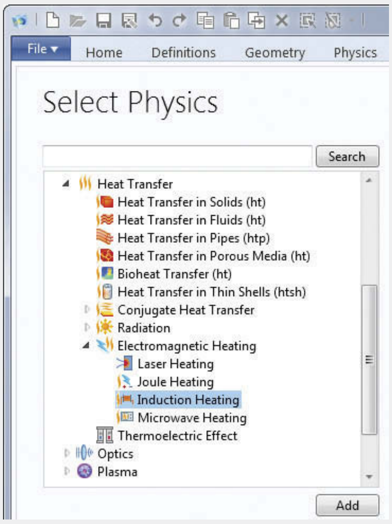


FIGURE 1: A multiphysics coupling is automatically created by selecting the predefined Induction Heating interface.

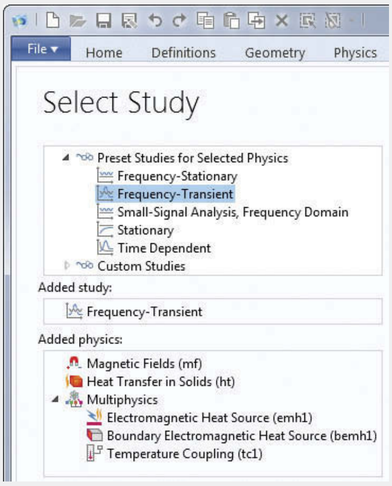


FIGURE 2: The Frequency-Transient study is used to compute temperature changes over time together with the electromagnetic field distribution in the frequency domain.

SIMULATION SOFTWARE BRINGS BIG CHANGES TO CABLE INDUSTRY

Multiphysics simulation has helped Prysmian generate new business and increase profits by delivering high-technology cables.

By **DEXTER JOHNSON**

PRYSMIAN GROUP IS a world leader in energy and telecom cables. The company's energy sector alone is made up of a wide range of products such as high-voltage cables for terrestrial and submarine applications; these include both alternating-current (HVAC) and direct-current (HVDC) systems.

Back in 2010, the R&D group at Prysmian made a big change in how it designs and tests new cables and systems. This shift is already producing dividends in terms of new revenues and increased profits. By fully adopting multiphysics simulation software, the group is able to optimize cable and systems designs for a wide range of harsh environments.

» MOVING BEYOND APPROXIMATIONS TO THERMAL SIMULATION

ONE IMPORTANT ASPECT to consider when designing a power transmission system is its ability to deliver the prescribed amount of current in steady-state conditions without exceeding the maximum permissible operating temperature. To address this point, a detailed thermal model of the system must be built that takes into account many variables: the structure of the cables and internal sources of electric losses (see Figure 1); the geometry of the installation; the installation environment (e.g., soil, water, forced or buoyant air); the ambient temperature; external loads due to solar radiation; and the system's proximity to other infrastructures.

Prior to using multiphysics simulation, Prysmian and others in the cable industry employed formulas or calculation methods provided by international standards. The standards work pretty well for those installations in which the cables are in an undisturbed thermal condition (typically, underground). But nowadays it is becoming common to have such systems installed in or crossing regions characterized by a so-called unfavorable thermal environment where, for example, the new cable system is in the vicinity of existing infrastructures such as other cables that cross the cable route.

Prysmian selected COMSOL Multiphysics® simulation software to build computer models that combine the structure of each cable, that of the power transmission system, the load conditions, and the conditions in the external environment to obtain realistic and reliable simulations (see Figure 2).

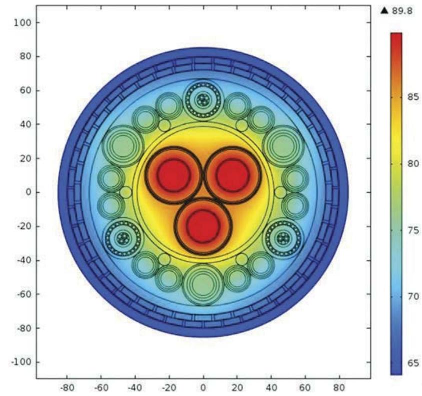


FIGURE 1: Cross-sectional view of the temperature distribution in a double-armored umbilical cable.

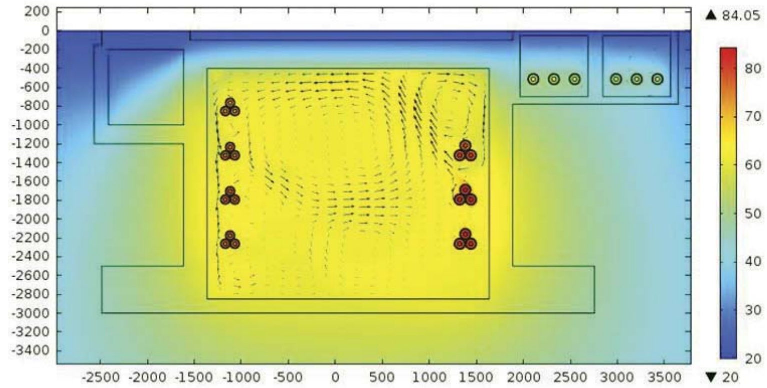


FIGURE 2: Using COMSOL Multiphysics, Prysmian combined thermal and computational fluid dynamics (CFD) analyses of high-voltage cable systems placed inside a horizontal tunnel with natural ventilation only.

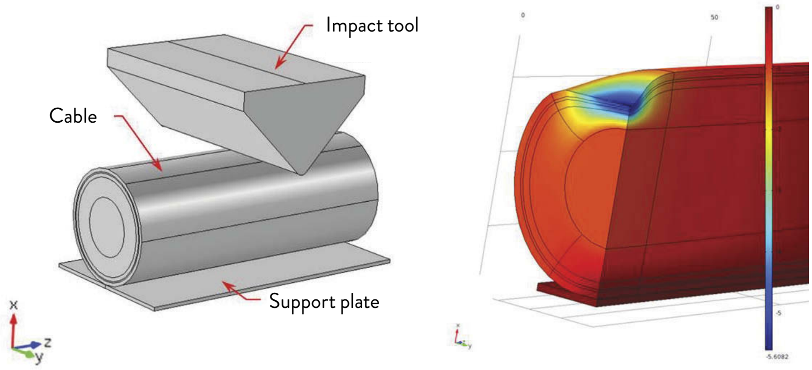


FIGURE 3: Simulation of an impact test on a medium-voltage cable.

"COMSOL is able to solve these kinds of problems because we can build a parametric model to optimize the geometry, the laying of the cables, and we can include the physics needed to account for the convection with the air," explains Massimo Bechis, Modeling and Simulation Specialist at Prysmian. "We can do extensive transient analyses to account for daily variations in solar irradiation and ambient temperature conditions. We can account for current load changes instead of considering constant operating conditions. This allows us to satisfy requests to consider transient conditions due to load changes. So multiphysics simulation really solves these kinds of problems that were very difficult or even impossible to do before."

» OPTIMIZING THE PROCESS OF MAINTAINING PERFECTION

NUMERICAL SIMULATIONS have already improved the way Bechis and his colleagues design some of Prysmian's most high-tech products. For example, parametric studies can be conducted to optimize the geometric dimensions or positioning of components in composite cables that may be made up of power conductors, cables for signal transmission, and hoses for delivery of fluid—all in the same structure. Bechis expects that progressive implementation of these methodologies will soon result in improved manufacturing processes as well.

Prior to using multiphysics simulation, many studies were done using mathematical tools developed internally by the company using commercial products such as Microsoft® Excel® or Visual Basic® and based on simplified models. By leveraging the know-how gained from the internally developed code when transitioning to new tools, Bechis is able to model at a much higher level of detail and with much greater accuracy for this kind of system. With COMSOL Multiphysics, Bechis says the company has taken a big step forward and improved the level of the services it can provide to both designers and customers.

"Now we have a lot of requests from colleagues because, for example, they know COMSOL is available to help them analyze and solve many thermal, electromagnetic, and structural problems," Bechis says.

Of course, prior to using simulation tools, Prysmian never had a cable fail. But in order to achieve that perfect record, a large design margin was built into every cable and system because of the calculation procedures adopted.

> "Multiphysics simulation really solves these kinds of problems that were very difficult or even impossible to do before."
> —**MASSIMO BECHIS, MODELING AND SIMULATION SPECIALIST, PRYSMIAN**

"Now we are able to optimize, among other things, the structure of our cables and still meet the specifications," says Bechis. "We can also explain why we use a certain amount of material in a certain layer and show how we came to our decisions based on the modeling."

With simulation, it is possible to perform the analysis of a test impact on a medium-voltage cable (see Figure 3). The ability to simulate this kind of test on a computer makes it possible to optimize the thickness and the kind of materials used in building the external layers of cables.

"We don't need to perform a lot of tests inside our laboratory," says Bechis. "Instead, we can do a lot of virtual tests on our computer. Then, when we are confident that we have found the optimum design for our cable, we can manufacture it and perform routine field tests in our laboratory."

Physical tests of actual prototypes are still performed, but the prototypes are much closer to the final design, and overall development time is therefore considerably shortened. These tests verify the mechanical behavior of the cables and systems so that the Prysmian team knows they can rely on their models.

» INCREASING PROFITS AND GENERATING NEW REVENUE

ONE OF THE clearest indications of the success of the new modeling tools is that Bechis and his colleagues have been able to respond to a lot of customer requests that specifically ask that there be simulation in addition to the standards that are normally used.

"We are now able to provide a better service," says Bechis. "We are saving money. We have improved procedures for designing our cables and power transmission systems. We have an additional and powerful way to respond to requests from clients."

Microsoft, Excel, and Visual Basic are registered trademarks of Microsoft Corporation in the United States and/or other countries.

DOUBLING BEAM INTENSITY UNLOCKS RARE OPPORTUNITIES FOR DISCOVERY AT FERMI NATIONAL ACCELERATOR LABORATORY

At Fermi National Accelerator Laboratory, upgrading the 40-year-old RF cavities in the Booster synchrotron will provide a twofold improvement in proton throughput for high-intensity particle physics experiments that could lead to breakthrough discoveries about the universe.

By **JENNIFER A. SEGUI**

PARTICLE ACCELERATORS SUCH as the Booster synchrotron at the Fermi National Accelerator Laboratory (FNAL) produce high-intensity proton beams for particle physics experiments that can ultimately reveal the secrets of the universe. High-intensity proton beams are required by experiments at the "intensity frontier" of particle physics research, where the availability of more particles improves the chances of observing extremely rare physical processes. In addition to their central role in particle physics experiments, particle accelerators have found widespread use in industrial, nuclear, environmental, and medical applications.

Radio frequency (RF) cavities are essential components of particle accelerators that, depending on the design, can perform multiple functions, including bunching, focusing, decelerating, and accelerating a beam of charged particles. Engineers Mohamed Awida Hassan and Timergali Khabiboulline, both from the Superconductivity and Radiofrequency Development Department of FNAL's Technical Division, are working in collaboration with John Reid from the Accelerator Division to model the RF cavities required for upgrading the 40-year old Booster synchrotron. Reid leads the rather complicated process to refurbish, test, and qualify the upgraded RF cavities.

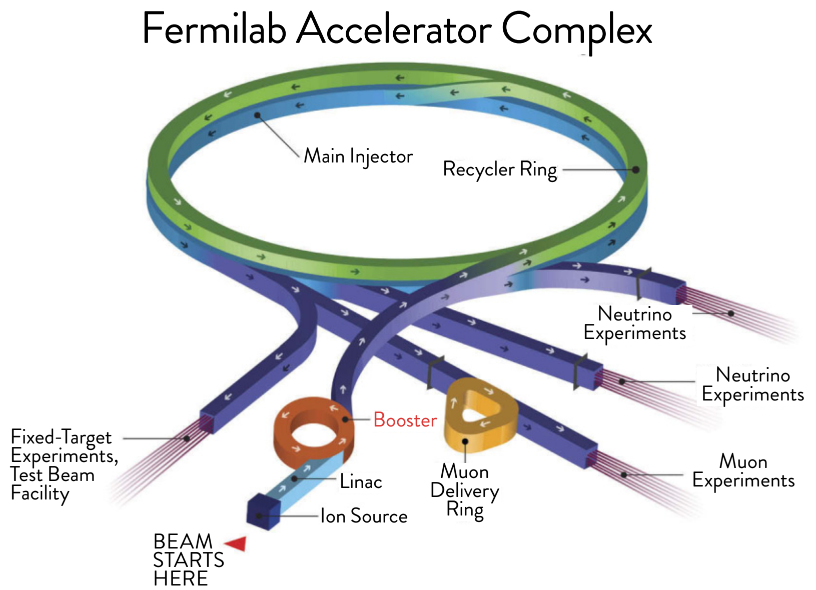
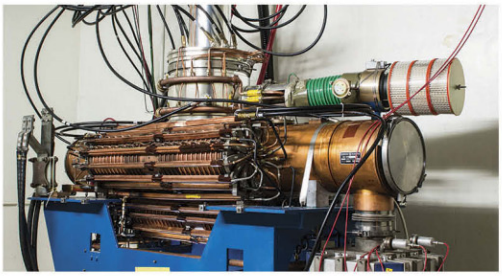


FIGURE 1: The FNAL accelerator chain showing the location of the Booster synchrotron.
IMAGES COURTESY OF FERMI NATIONAL ACCELERATOR LABORATORY

"In our work, we demonstrate the early-stage feasibility of the upgraded RF cavities to sustain an increased repetition rate of the RF field required to produce proton beams at double the current intensity," says Hassan. "We are using both multiphysics simulation and physical measurements, provided by our colleagues in the Accelerator Division, to evaluate the RF, thermal, and mechanical properties of the Booster RF cavities."

» POWERING PARTICLE PHYSICS RESEARCH

FNAL IS CURRENTLY enacting its Proton Improvement Plan (PIP), under the leadership of William Pellico and Robert Zwaska. The plan calls for facility upgrades in order to double the beam throughput and modernize the particle accelerators. A schematic of the accelerator



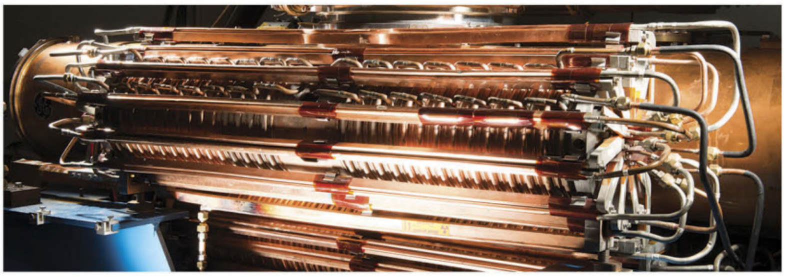


FIGURE 2: At left, a photograph of a copper ferrite-tuned RF cavity from FNAL's Booster synchrotron. At right, a ferrite tuner.

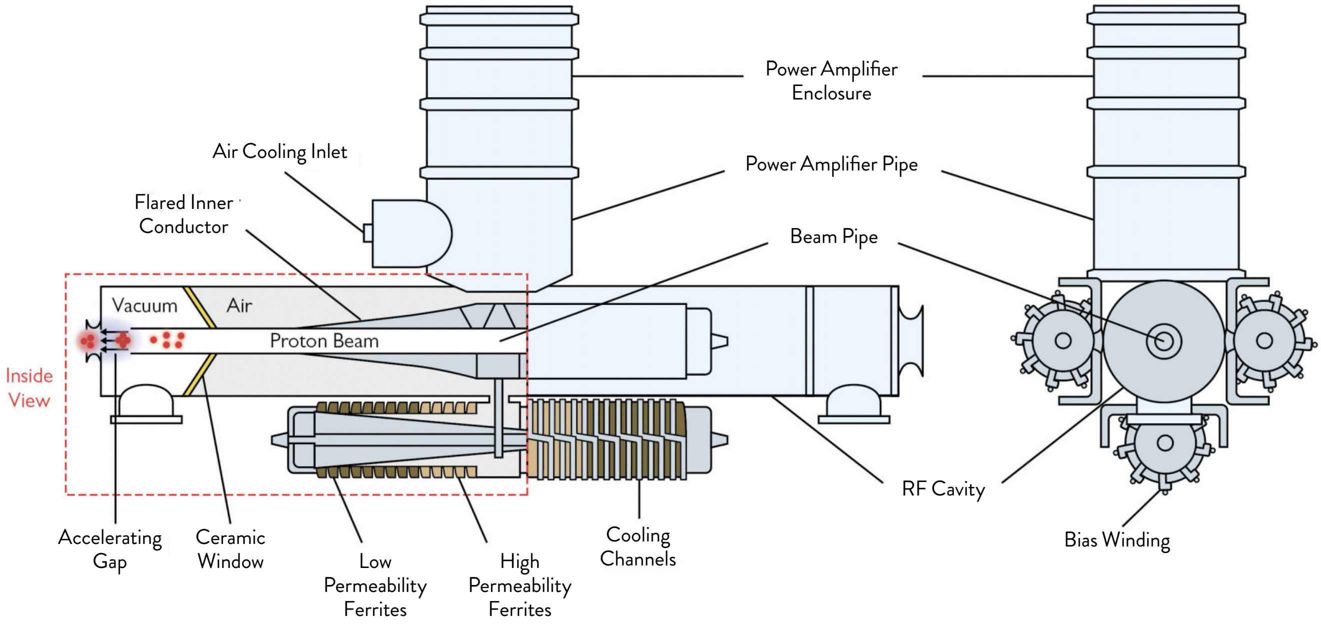


FIGURE 3: Front- and side-view drawings of a Booster RF cavity with three ferrite tuners and a tetrode power amplifier. The side-view drawing shows the high- and low-permeability ferrites, including the cooling channels required to prevent overheating. The ferrites are enclosed in a copper tube that has been eliminated in this drawing in order to expose more detail.

chain at FNAL is shown in Figure 1. The Booster synchrotron, a cyclic particle accelerator and intermediate stage in the particle accelerator chain, is shown in red in the figure. Located about 20 feet below ground, the Booster uses magnetic fields to bend the proton beam in a circular path while 19 ferrite-tuned RF cavities accelerate the protons to 20 times their initial energy when first arriving at the Booster. The protons are transferred to the Main Injector synchrotron, where they are further accelerated, and then directed to multiple underground beam lines. Protons in the underground beam lines interact with neutrino production targets, experimental target materials, or detectors as part of testing.

» THE WORKHORSE OF THE BOOSTER SYNCHROTRON

ONE OF THE remaining challenges of the PIP is upgrading the RF cavities of the Booster synchrotron so they can handle the higher-intensity beams. A photograph of a Booster RF cavity is shown in Figure 2. The Booster RF cavities are half-wave resonators that generate an oscillating electromagnetic field to accelerate protons along the central beam pipe. Each RF cavity is loaded with three coaxial ferrite tuners placed at 90-degree intervals to achieve sufficiently low power loss density per tuner. In the fourth position, a tetrode power amplifier

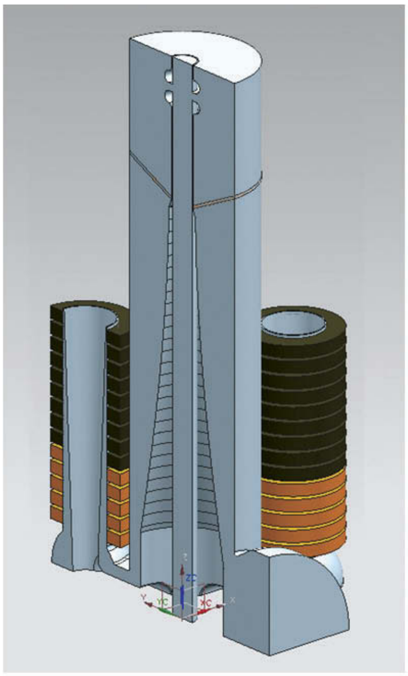


FIGURE 4: RF model geometry for the Booster RF cavity with ferrite tuners. One-quarter of the symmetric cavity design was modeled and imported into COMSOL.

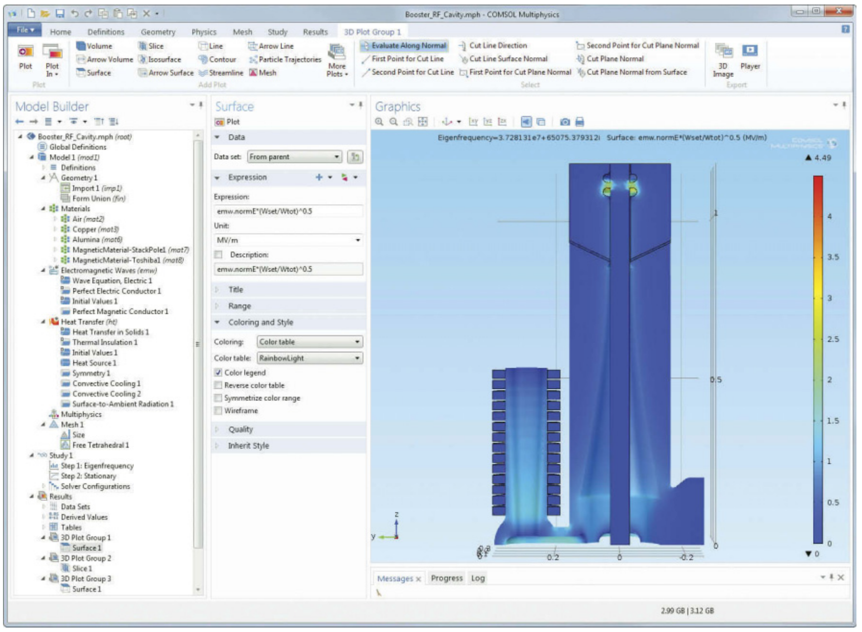


FIGURE 5: This COMSOL Desktop® image shows model setup and analysis for a multiphysics model of an RF cavity. The geometry, materials, physics, and study are defined in the Model Builder window at left. A surface plot of the electric field on the RF cavity and tuner is displayed in the Graphics window. RF analysis is initially conducted to capture the electric and magnetic fields that will be used later as sources of heating in the thermal analysis. The electric field distribution was also investigated to ensure that breakdown will not occur near the high-field regions in air or under vacuum.

supplies the RF signal. Side- and front-view drawings of the Booster RF cavity are shown in Figure 3.

The RF cavities are designed with a specific size and shape in order to allow tuning of the resonant frequency from 37 MHz to 53 MHz. As protons cycle through the Booster, the frequency is gradually increased by varying the bias on the ferrite tuners to accelerate the particles up to the target energy. The operating frequency range of the RF cavities will not change as part of the PIP. Parameters such as the accelerating voltage and beam repetition rate, which governs how often particle beams are produced and sent through the accelerator chain, do need to increase, however.

» SIMULATION QUANTIFIES RF HEATING

OPERATING THE BOOSTER RF cavities at the higher repetition rate and accelerating voltage is necessary in order to increase the overall efficiency of the particle accelerators and double the hourly proton yield. An increase in the power dissipated in the RF cavities is projected, however, which could lead to overheating. Additional thermal stress in the cavity and tuners could potentially reduce their lifetime and produce an unreliable proton yield. Better cooling may be required to ensure stable long-term proton production at the desired rate. The current cooling mechanism uses water circulating in pipes surrounding the cavities in addition to fans that generate a cooling air flow.

Hassan and Khabiboulline are evaluating the Booster RF cavities to estimate the cooling requirements at the increased repetition rate and accelerating voltage. Physical measurements of temperature in the RF cavity and tuner can be difficult to acquire and are often inaccurate. Multiphysics simulations were used in conjunction with experiments to develop a model of the RF cavity that could be used to evaluate its RF, mechanical, and thermal properties. The model was set up in COMSOL Multiphysics®, where one-quarter of the actual geometry was imported from an SAT® file that was created in a separate CAD program. The imported model geometry is shown in Figure 4 and includes the cavity and tuners. “We chose to simulate only part of the symmetric design to reduce the computational complexity and time required to solve the model,” says Hassan. “Perfect magnetic conductor (PMC) boundary conditions were enforced along the symmetry planes while the perfect electric conductor (PEC) boundary condition was enforced on all other boundaries in the RF model.”

The materials, physics, and study were set up as shown in the model tree in Figure 5. The copper material for the walls was defined using the built-in material properties available in the Material Library. The properties of the ferrite mate-

SAT is a registered trademark of Spatial Corporation.

From left to right, the engineers behind the Proton Improvement Plan and RF cavity simulations: Robert Zwaska, PIP deputy leader; William Pellico, PIP leader; Mohamed Hassan, senior RF engineer; and Timergali Khabiboulline, RF Group leader. They are pictured in the Booster synchrotron tunnel at FNAL, next to a ferrite-tuned RF cavity. John Reid, not pictured, is the RF Group Leader from the Accelerator Division.

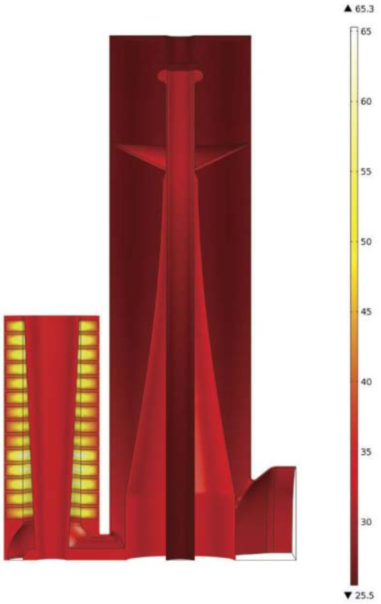


FIGURE 6: A surface plot of temperature is shown from the thermal analysis of an FNAL Booster RF cavity at 55 kV accelerating voltage and 7 Hz repetition rate.

rial for the tuners were custom-defined. Initially, the electromagnetic problem was evaluated to solve for the electric and magnetic fields. Electromagnetic losses in the ferrite and resistive losses along the cavity surface were used as heat sources for solving the heat transfer problem. The cooling mechanism was incorporated into the model by applying the convective cooling boundary condition to the outer walls of the tuner. The model was validated by comparing the measured quality factor (Q) of the RF cavity with the quality factor computed in the COMSOL® environment.

Thermal analysis was performed to show the effect of increasing the repetition rate and accelerating voltage on the operating temperature of the tuners. The results shown in Figure 6 are for an accelerating voltage of 55 kV and repetition rate of 7 Hz where a temperature maximum of 65°C was observed in the tuners. The accelerating voltage was held constant at 55 kV, while the repetition rate was increased from 7 to 15 Hz. The analysis showed that this approximate doubling of the repetition rate could cause the operating temperature of the tuners to increase by more than 30°C. A further increase in the accelerating voltage to 60 kV while operating at the 15 Hz repetition rate could cause the operating temperature to increase by another 10°C. The power dissipated in the RF cavity and tuners increased from 16.6 kW at 55 kV and 7 Hz repetition rate to 39.1 kW at 60 kV and 15 Hz repetition rate.

» ENSURING SMOOTH OPERATION THROUGH 2025

BASED ON THE simulation results, Hassan confirms that “the cooling mechanism will need to be upgraded along with the cavities to handle the increased repetition rate and accelerating voltage through 2025 as called for in the Proton Improvement Plan.” Increasing the airflow will be one of the first adjustments made, although adding more pipes, further reducing the water temperature, and experimenting with the water flow rate are all possibilities. The RF cavity model will be expanded in the future to include air and pipe flow so that the geometry and cooling mechanism more closely represents that of the actual RF cavity.

In the extreme environment of the Booster synchrotron, radiation hazards and high temperatures make upgrading the RF cavities a challenge. Simulation results are being used to facilitate design decisions with regard to the cooling mechanism to help reduce the time, risks, and expense associated with the upgrade and continued use of the RF cavities. Successfully implementing the improved cooling system will aid in keeping the unique RF cavities of the Booster synchrotron operational through their 55th year and accelerating even more high-energy protons. ◎

MODELING OF COMPLEX PHYSICS SPEEDS CHIP DEVELOPMENT

The symbiotic relationship between computer chips and computational modeling helps keep Moore's Law on pace at Lam Research Corporation.

By **GARY DAGASTINE**

IN 1965, Gordon Moore predicted that ongoing technological advances would lead to a doubling of the number of transistors on computer chips about every two years, slashing the computing cost per calculation and exponentially increasing computing power.

But while more powerful chips are driving advances in computational modeling, the reverse is also true: Computational modeling is in turn driving progressively higher transistor densities and better architectures, reliability, and processing speeds. This virtuous circle is helping the semiconductor industry stay on pace with Moore's Law.

Lam Research Corporation is one of the world's leading suppliers of semiconductor manufacturing equipment and services. Its products are used to etch, deposit, and clean the ultrathin material layers from which semiconductors are built.

To meet the demands of the fast-paced semiconductor industry, Lam continually increases the performance, reliability, and availability of its products while also keeping their capital costs as low as possible. Many departments at Lam use computational modeling for the detailed analyses of nanoscale transistor features, to assess the performance of equipment, and for continuous product improvement involving many different scale levels.

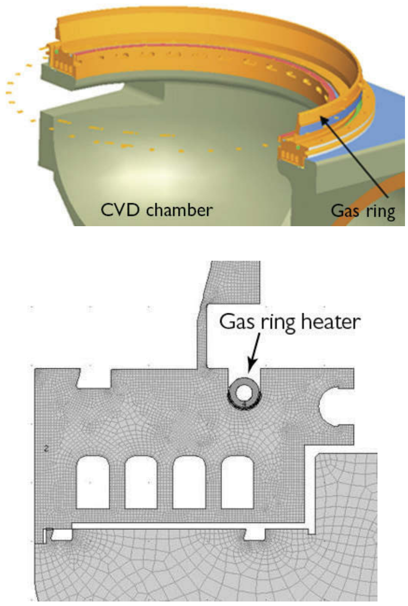


FIGURE 1: Gas is introduced into a chemical vapor deposition (CVD) chamber via a gas ring. The challenge is to keep the temperature of the ring uniform throughout the entire processing sequence.

The company's Computational Modeling and Reliability Group, headed by Peter Woytowitz, serves as a centralized internal resource for product research, development, and support. "Lam's goal is to be first to market with the best technology, but because our customers' processes and needs are constantly changing it's imperative for us to be fast and efficient. COMSOL Multiphysics helps us do that," he noted.

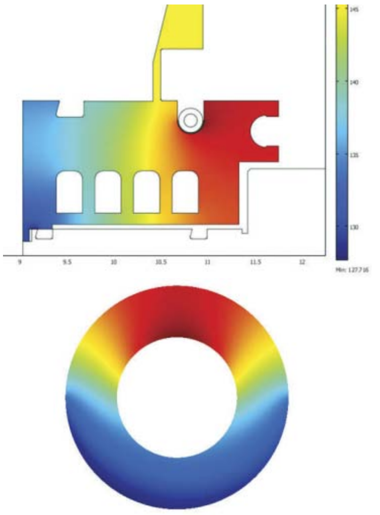


FIGURE 2: Lam is using the Heat Transfer Module in COMSOL Multiphysics® to help predict temperature uniformity under various operating conditions for CVD chamber gas ring heaters.

» SIMULATION LEADS TO BETTER CONTROL OF TEMPERATURE UNIFORMITY

IN SEMICONDUCTOR manufacturing, integrated circuits are fabricated on a wafer of semiconducting material. The circuits are built from multiple layers of different conducting and insulating materials that must follow an extremely precise design. These layers—some now only a few nanometers thick—are created via a series of many different processes that involve multiple aspects of material deposition, patterning, and selective removal.

Among the equipment used to deposit these layers, or thin films, of material onto a wafer are chemical vapor deposition (CVD) tools. A wafer is placed into a sealed CVD chamber for processing, and gas containing the material to be deposited is introduced to the chamber. In one design, this is done via a gas ring that distributes the gas uniformly throughout the chamber (see Figure 1). The gas is energized to its plasma state to help drive the material onto the wafer and is then exhausted from the chamber.

It's imperative that the temperature of the gas ring be both uniform and hot enough throughout the entire process to minimize the amount of material deposited on it. If the desired temperature control is not achieved, then repeated thermal cycling can cause microscopic particles to break off the ring and fall onto a wafer, creating defects that could ruin the wafer. Particles are one of the leading causes of defects on otherwise good—and expensive—wafers in progress.

Using simulation, engineers design the heating and cooling channels within the gas ring, as well as an external heater to control gas ring temperature accurately during all phases of the CVD process. This entails both cooling the ring during plasma heating and heating it appropriately at other times (see Figure 2).

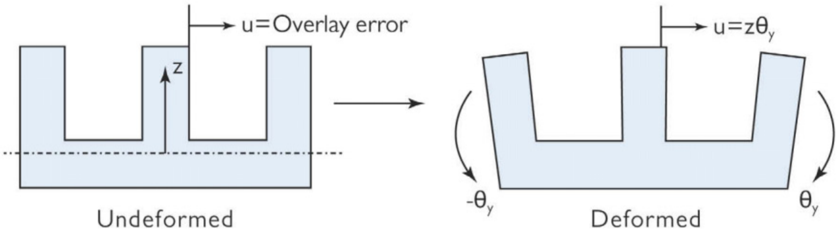


FIGURE 3: The cross-section at left shows an undeformed structure that introduces no photolithographic overlay error. On the right, a semiconductor wafer deformed by various stresses tilts, thereby introducing overlay error.

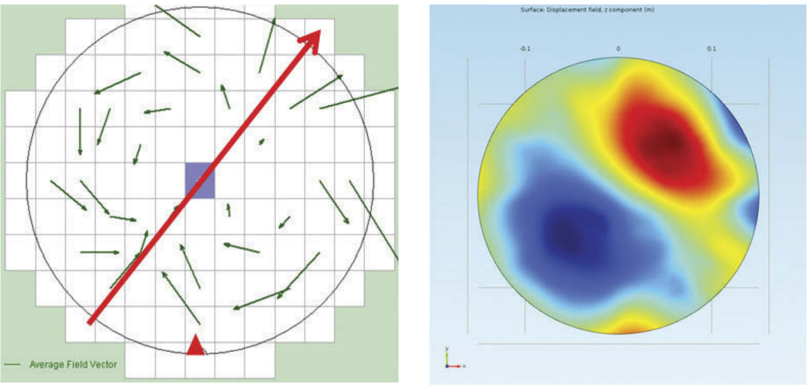


FIGURE 4: At left is a map of vectors contributing to wafer bow. The software resolved them into wafer displacement contour maps. On the right is a view in the x-y plane.

» MAJOR INSIGHTS GAINED INTO WAFER DEFORMATION IMPACTS

ANOTHER PROJECT at Lam was to study the effects of wafer deformations on photolithography, a key chip-manufacturing process similar to the process by which a photograph is developed on photosensitive paper.

During photolithography, light shines through a pattern known as a mask onto a photosensitive semiconductor wafer surface, and a layer of material is deposited onto and/or etched into the wafer according to the mask pattern. A series of masks are used to successively pattern layers until the integrated circuit is complete.

With the feature sizes on advanced chips now measuring 22 nanometers or less, many seemingly minor wafer distortions can have major deleterious effects on patterning accuracy. "Minute distortions of the wafer can cause misalignment and can distort features," describes Woytowitz. "This can then affect the ability of the photolithography process to accurately align and pattern the wafer."

Using COMSOL, analysts can identify any deviations from the desired pattern, called overlay error (see Figure 3), to determine if these defects were caused during the manufactur-

> *"Lam's goal is to be first to market with the best technology, but because our customers' processes and needs are constantly changing it's imperative for us to be fast and efficient. COMSOL Multiphysics helps us do that."*
>
> —PETER WOYTOWITZ, DIRECTOR OF ENGINEERING, LAM RESEARCH CORP.

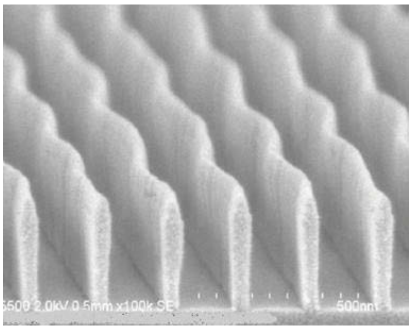


FIGURE 5: Photomicrograph showing the buckling of dummy structures used as building blocks to fabricate high aspect ratio interconnect for advanced computer chips.

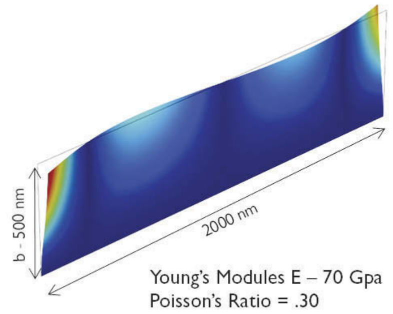


FIGURE 6: The Structural Mechanics Module in COMSOL Multiphysics can predict how buckling will occur in high aspect ratio chip interconnect.

ing process. If so, the performance of those tools can be optimized.

Woytowitz's group uses simulation to study how Lam's tools affect wafer deformation and then to determine if these deformations would impact photolithography. Plate theory, in conjunction with plate elements, is used to help characterize and correlate these distortions with measurable overlay errors.

For example, physical displacement from the horizontal plane, or wafer bow, is a significant contributor to overlay error. Before photolithographic processing, semiconductor wafers typically exhibit a bow of as much as 100 µm. Even when electrostatically bound to a tool's chuck for processing, or "clamped," they still may displace about 1 µm (see Figure 4).

Through simulation, Lam has determined that 1 µm of wafer bow generates overlay errors of about 10 nm. Since allowable overlay errors on today's advanced chips are generally about 10 nm (although they can be less), that is right at the allowable limit. Instead of a difficult and time-consuming trial-and-error testing process, simulation helped to quickly and precisely correlate the degree of wafer bow with overlay error.

» SUSCEPTIBILITY TO BUCKLING CAN NOW BE PREDICTED

THE USE OF high aspect ratio structures and features on today's chips is growing in order to save space, particularly for the metal lines known as interconnects that connect a chip's transistors.

The fabrication of interconnect is a multistep process. First, temporary lines are built from a film such as amorphous carbon by first depositing the material, then etching a series of closely spaced trenches into the film. Next, the trenches are filled with a dielectric (insulating) material, the temporary structures are etched away, and metal is deposited into the now-vacant spaces, forming tall, thin lines of metal interconnect.

However, manufacturers found that sometimes the temporary structures would buckle (see Figure 5). This buckling was not well understood, but if it could be predicted, then Lam could determine which high aspect ratio geometries would be successful in a production environment.

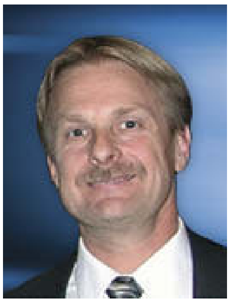
Woytowitz's group theorized that the buckling resulted from intrinsic compressive stress or possibly from mismatching coefficients of thermal expansion.

To investigate, they built COMSOL models, taking into account Young's modulus, for measuring the stiffness of an elastic material, and Poisson's ratio, the ratio of transverse to lateral strain. They compared these results with experimental values.

Analysis to date confirms that it is largely a buckling problem, and with an appropriate adjustment factor to correlate theory to experimental data, simulation can be used to predict when and how buckling will occur (see Figure 6).

» MODELING IS AN INCREASINGLY IMPORTANT TOOL

"COMPUTATIONAL MODELING is playing an increasingly important role at Lam, and we rely heavily on it," Woytowitz concludes. "COMSOL isn't the only tool we use, but its accuracy, ease of use, and the common look and feel of its user interface for many different physics domains allow us to become productive with it much more quickly and deeply than with other tools. These projects are just a few examples of how we are putting it to use." ◎



In addition to the individuals named in this article, thanks and acknowledgment go to all the technologists, engineers, and managers at Lam Research Corporation for their involvement and support in computational modeling. In particular, thanks go to Lam engineers **RAVI PATIL**, *for work associated with the gas ring (Figures 1 and 2), and to* **KEERTHI GOWDARU**, *for work associated with line-bending analysis (Figures 5 and 6).*

Peter Woytowitz, Director of Engineering, Lam Research Corp.

MEETING HIGH-SPEED COMMUNICATIONS ENERGY DEMANDS THROUGH SIMULATION

Simulation-driven design is employed at Bell Labs Research to meet the energy demands of exponentially growing data networks and reduce the operational energy costs of the telecommunications network.

By **DEXTER JOHNSON**

ENERGY DEMANDS ARE becoming a bottleneck across multiple industries. From reducing the energy costs associated with operating a building to maintaining the exponential growth of high-speed networks, energy considerations are critical to success. Significantly improved energy efficiency is driving researchers at Bell Labs to design and implement new technologies in a scalable and energy-efficient way.

Bell Labs is the research arm of Alcatel-Lucent and is one of the world's foremost technology research institutes. Bell Labs Alcatel-Lucent founded the GreenTouch consortium, a leading organization for researchers dedicated to reducing the carbon footprint of information and communications technology (ICT) devices, platforms, and networks. The goal of GreenTouch is to deliver and demonstrate key components needed to increase network energy efficiency by a factor of 1000 compared with 2010 levels.

The Thermal Management and Energy Harvesting Research Group at Bell Labs (Dublin, Ireland) leads Alcatel-Lucent's longer-term research into electronics cooling and energy-harvesting technology development. It has developed two new energy-saving approaches that promise significant savings.

One research project is targeting between 50 and 70 percent energy reduction by improving the thermal management surrounding the photonic systems by means of which laser light transmits data through our networks. Meanwhile, another team has developed an entirely new approach to the harvesting of energy from ambient vibrations that generates up to 11 times more power than current approaches and is used to power wireless sensors for monitoring the energy usage of large facilities.

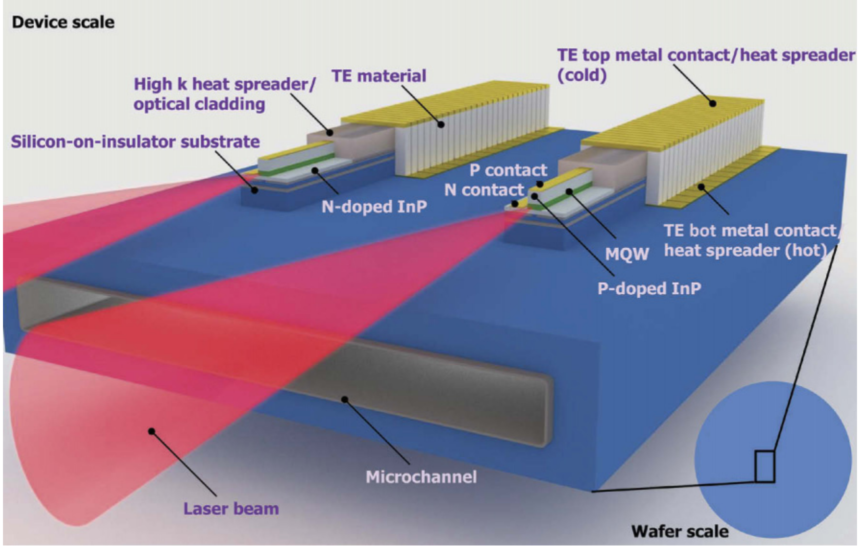


FIGURE 1: Schematic of the thermally integrated photonics system (TIPS) architecture, which includes microthermoelectric and microfluidic components.

» USING SIMULATION TO MEET DATA TRAFFIC DEMAND WITH PHOTONICS COOLING

THE EXPLOSION IN data traffic in the last few years is causing an immense strain on the current network, which was designed for low cost and coverage rather than energy efficiency. Energy management is becoming a major obstacle to the deployment of next-generation telecommunication products.

To address this issue, the Thermal Management team investigates all aspects of electronics and photonics cooling. The research team is realizing benefits that affect product performance by employing multiphysics simulation at multiple length scales—from the micrometer scale to the macro level.

To find efficiencies at the micrometer scale, Bell Labs has turned to COMSOL Multiphysics® to model potential approaches for cooling photonic devices that rely on the thermoelectric effect. Thermoelectric

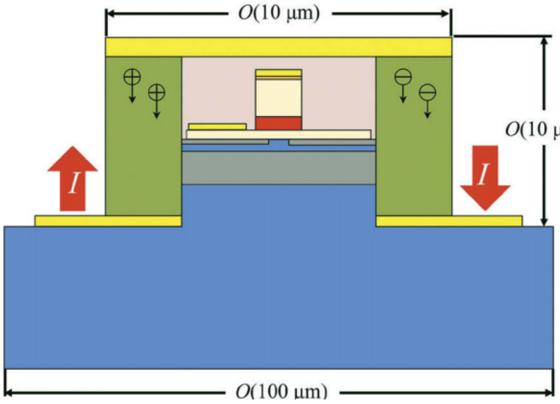


FIGURE 2: Cross-section schematic of laser architecture with integrated µTEC (not to scale).

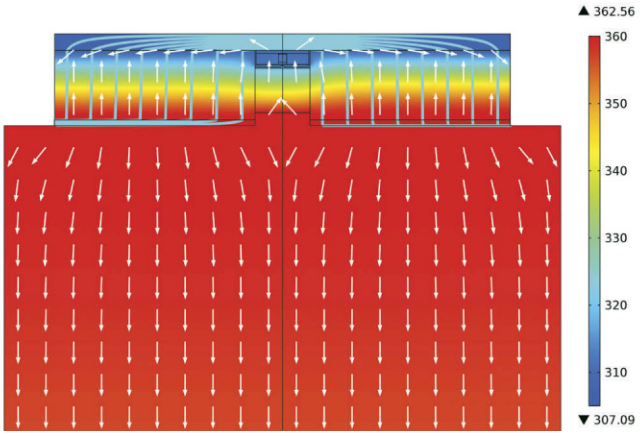


FIGURE 3: Multiphysics simulation of a laser with an integrated µTEC where temperature (surface plot), current density (streamlines), and heat flux (surface arrows) are shown.

materials are those in which a temperature difference is created when an electric current is supplied to the material, resulting in one side of the material heating up and the other side cooling down to provide heat pumping against an adverse temperature gradient. This effect can be employed to provide high-precision temperature control of photonics devices and forms one of the core building blocks within a novel architecture called a thermally integrated photonics system (TIPS), as depicted conceptually in Figure 1. Using the TIPS architecture, the team has simulated the electrical, optical, and thermal performance of new laser devices with the integrated microthermoelectric coolers (µTECs), as shown in Figure 2. Such µTECs have the potential to be applied in telecommunication laser devices that require cooling to maintain their design output wavelength, output optical power, and data transmission rates. Simulation results from COMSOL Multiphysics are shown in Figure 3 and help optimize the system design. The challenges in cooling photonics devices include precise temperature control, extremely high local heat fluxes, and micrometer-size features that need to be cooled. In particular, the research team investigated how precise temperature control and refrigeration are maintained in these systems through µTECs that are integrated with semiconductor laser architectures.

"COMSOL is the best simulation software solution for simultaneously solving all the physical processes associated with advanced photonic integrated circuits," says Shenghui Lei, one of the Bell Labs team members looking at photonics cooling. "The reason for this is that thermoelectric effects—Peltier, Thomson, and Seebeck—and the resulting temperature and electrical fields are all coupled within the same simulation environment, COMSOL. This provides deeper physical insight into the problem."

Another key COMSOL functionality is the link between COMSOL and MATLAB® through the LiveLink™ interface. This link lets the team accelerate the design phase by accurately modeling different parts of the package with design rules in MATLAB®.

"If we look at the length scales of typical lasers used in photonics devices, you are talking about micrometers to tens of micrometers," says Ryan Enright, TIPS technical lead at Bell Labs. "However, laser performance is coupled from that scale all the way up the thermal chain until you get to the ambient air on the board. Solving complicated multiphysics problems across multiple length scales is computationally expensive. So we value the functionality of being able to use COMSOL and MATLAB® together to provide insight into the role of system design on laser performance in a computationally efficient way."

Domhnaill Hernon, Research Activity Lead at Alcatel-Lucent, further explains that, beyond just capturing the thermal behavior of integrated thermoelectrics, by carefully validating simulations against experimental device performance data it's also possible to more precisely determine the region of

> "COMSOL is the best simulation software solution for simultaneously solving all the physical processes associated with advanced photonic integrated circuits."
>
> **—SHENGHUI LEI, BELL LABS**

MATLAB is a registered trademark of The MathWorks, Inc.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

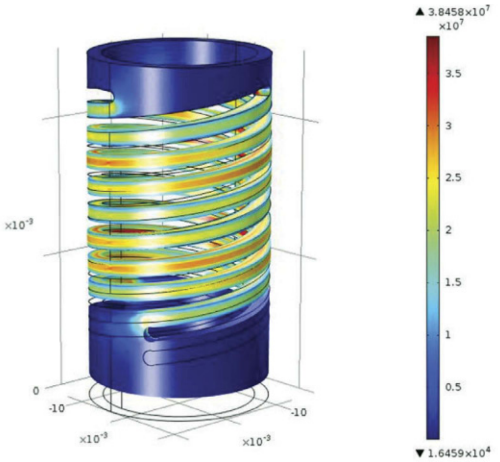


FIGURE 4: Left: Prototype of novel machined-spring energy harvester. Right: Simulation of the energy harvester, showing von Mises stress.

the laser device that caused the heat generation in the first place.

"It's the capability of accurately modeling the heat generation source and then coupling that to the device- and system-level cooling solutions where we see the power of COMSOL," says Hernon.

» OPTIMIZING A NEW ENERGY-HARVESTING DEVICE

PHOTONICS COOLING IS not the only way that Bell Labs is addressing energy concerns. Simulation is also enabling wireless sensors to be powered autonomously, reducing the need to frequently replace batteries in a network. Large-scale commercial deployments of wireless sensors have been hindered by costs associated with battery replacements.

The Bell Labs Energy Harvesting team developed a solution that efficiently converts ambient vibrations from motors, AC, HVAC, and so on to useful energy. In this way, a wireless sensor can potentially be powered indefinitely. Energy-harvesting technology can be employed in many different ways with low-power wireless sensors in applications ranging from monitoring energy usage in large facilities to enabling the large-scale sensor deployments of the future Internet of Things (IoT).

The energy-harvesting devices designed at Bell Labs operate by converting vibrations into electricity thanks to electromagnetic induction. Traditionally, energy harvesters consist of a single magnet that moves inside a coil, thus inducing a current.

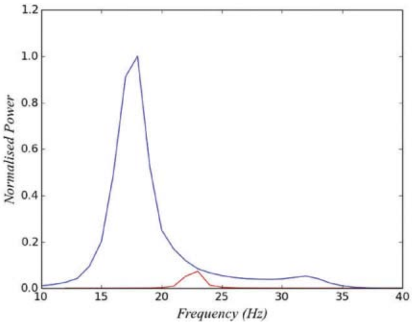


FIGURE 5: The figure compares the Bell Labs design (blue line) with a similar state-of-the-art single-mass system (red line). The multiple-mass system designed by Bell Labs has 11 times greater peak energy.

The team employed simple physical principles: the conservation of momentum and velocity amplification. The design they developed uses multiple masses, or what is called multiple degrees of freedom, and can significantly amplify the velocity of the smallest mass in the system. This novel energy-harvesting device is now being investigated, as it is more efficient at converting ambient vibrations into electrical current than similar technology that does not employ the multiple-degree-of-freedom approach.

COMSOL is used for modeling the magnetic, electrical, and structural behavior of this system. See Figure 4, left for a picture of the energy harvester prototype and Figure 4, right for simulation results.

"We are using COMSOL to examine the electromagnetic coupling and the magnetic field distribution," says Ronan Frizzell, the lead researcher on this topic. "We've used the parametric sweep capabilities of COMSOL to optimize the system configuration and better understand the system dynamics."

A parametric sweep allows for the understanding of how the performance of the system is affected if you change one of its components, such as a spring or a magnet orientation. Figure 5 shows experimental results for the novel energy-harvesting device whose design process made use of COMSOL to achieve an enhanced understanding of the system dynamics involved.

"Reasonably quickly we can go through a parametric sweep, and by that I mean looking at structural, electrical, and magnetic parameters that are important to the system and how they couple together and affect each other," says Hernon. "That's very important. We don't look at them separately, but we use COMSOL to look at them in a coupled way. It's important for optimizing the system for real-life deployment."

While these technologies are not yet in commercial use, Hernon and his colleagues are confident they are getting a level of accuracy in the models for these new technologies that could only have been reached before by using much more time-consuming and laborious methods. At this pace of development, Hernon believes that the new thermoelectric cooling methods and innovative energy-harvesting devices should see commercial use in as little as five years. ◎

NANORESONATORS GET NEW TOOLS FOR THEIR CHARACTERIZATION

Nanoresonators offer optical science a new subwavelength tool to control light, and at Institut d'Optique d'Aquitaine, we have developed a method to gain new insights into their properties.

By **JIANJI YANG,** post doctorate at Laboratoire Photonique, Numérique et Nanosciences (LP2N), **MATHIAS PERRIN,** CNRS scientist at Laboratoire Ondes et Matière d'Aquitaine (LOMA) and **PHILIPPE LALANNE,** Directeur de Recherche at LP2N

AT THE LABORATOIRE PHOTONIQUE, Numérique, et Nanosciences of the Université de Bordeaux in France, we have been working to develop a method for understanding and predicting the interaction of light with matter at the subwavelength scale.

We have implemented a numerical tool based on electrodynamics equations using COMSOL Multiphysics®, its RF Module, and MATLAB®. Simulation is particularly useful for developing and operating the emerging technology known as nanoresonators, or optical nanoantennas. Theory, analytical solutions, and simulation provide great insights into how these devices operate and shorten their development time. This will favor the use of nanoresonators in applications ranging from photovoltaics to spectroscopy.

» WHY ARE NANORESONATORS USEFUL?

THE INTRODUCTION OF nanoresonators has been a relatively recent event in optics. These devices manage the concentration, absorption, and radiation of light at the nanometer scale in much the same way as it is accomplished with microwaves at much larger scales. An example of an optical nanoantenna is given in Figure 1, where a source, placed in between two gold nanospheres, is coupled to the far field more strongly than if it were alone in vacuum. Typically, the shape of the antenna can control the radiation. For example, Figure 2 shows how a silver sphere illuminated by a plane wave influences the scattered near-field.

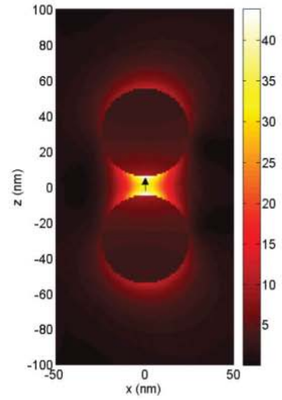


FIGURE 1: Example of nano-antenna: Intensity of electric field radiated by a gold sphere doublet coupled to a dipolar source (represented with a black arrow). The sphere radii are only 25 nanometers, and the distance between the spheres is 10 nm. The power radiated by the source is much larger than the power that would be radiated by the same source in the absence of the spheres. The radiation diagram in the far field can be controlled by tailoring the shape of the antenna. All dimensions are much smaller than the emission wavelength of 505 nm.

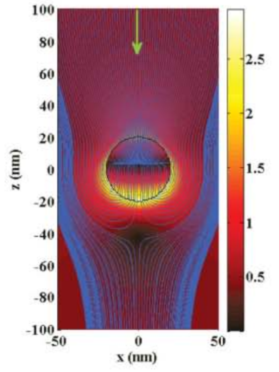


FIGURE 2: Intensity of the electric field around a single silver sphere with a radius of 20 nm illuminated by a plane wave incident from the top (the green arrow indicates the direction of propagation). The flux lines are represented in blue.

» MODELING ELECTRODYNAMICS IN NANORESONATORS

SINCE NANORESONATORS are essentially made of metal and can have different shapes, their simulation should rely on a software that can represent their geometry and model their electromagnetic properties accurately.

However, the electromagnetic properties of metal are not so easy to model, especially when you are solving for problems in the time domain and with complicated shapes like small, oddly shaped objects with curves and sharp corners that are also very close together. To model such complex nanoresonators, we rely on the finite element method (FEM) to achieve accurate predictions. And with COMSOL, one can get very good numerical representations of the curved surfaces and corners and of the volume involved in the computation, so it's quite convenient and appropriate.

Until very recently, the state of the art was to solve Maxwell's equations for a

MATLAB is a registered trademark of The MathWorks, Inc.

particular excitation, i.e., for a given incidence, wavelength, and polarization of a light beam impinging on a resonator.

However, when using such an approach, the whole numerical simulation has to be redone each time the excitation field changes. The numerical load may then be too heavy to fully characterize the nanoresonator, and above all, the computed results obtained with brute-force calculations may still hide a great deal of knowledge about the physical mechanisms at play.

» A NEW ANALYTICAL-NUMERICAL METHOD FOR CHARACTERIZING NANORESONATORS

USING THE STRIKING of a bell as an analogy for light excitation of a nanoresonator, it is possible to understand that any hammer stroke will more or less excite the same vibration modes of a bell. The latter represents an intrinsic characteristic of the resonator that does not depend on the excitation. If one is able to find these modes and understand how they are excited, then it is possible to describe the interactions between the resonator and its environment much more easily and intuitively and without the need to rely on brute-force calculations. Very rapidly, we realized how helpful it was to have a modal theory to describe our resonators.

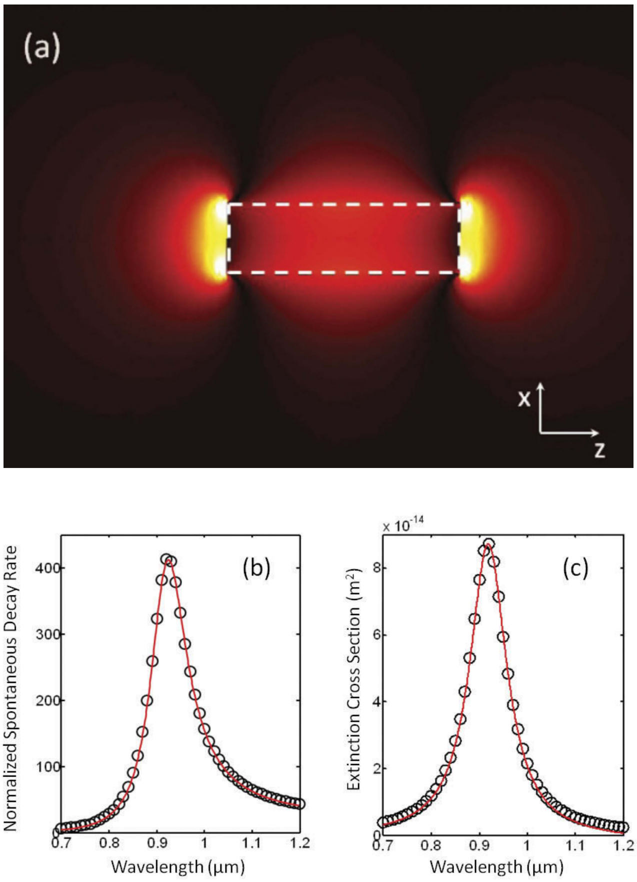


FIGURE 3: (a) Distribution of z-component of the electrical field |Ez| for the normalized quasinormal mode of a cylindrical gold nanorod with a diameter of 30 nm and a length of 100 nm. The white dashed line represents the rod contour. (b) Spontaneous decay rate of a cold molecule located on the rod axis at a 10 nm distance from the rod. (c) Attenuation cross section of the rod under illumination by a plane wave polarized along its axis. In (b) and (c), black circles are fully vectorial computational results obtained with COMSOL. Each point requires an independent calculation. Simulation results are in good agreement with the predictions of the analytical model represented by the solid red curves.

Our initial contributions were more theoretical. We knew that if you hit a nanoresonator with light, you are going to excite its resonance modes, which is obvious. Defining what the excitation strength is analytically, however, was not obvious. Using COMSOL, we created a tool that calculates the modes and their excitations quite easily and solved this long-standing problem.

We were able to use COMSOL both to compute the response of the system to a particular excitation and to compute the modes of the nanoresonator. The fact that COMSOL can easily be interfaced with MATLAB® was an essential point for us, as our COMSOL simulation could be integrated as the field-computing engine of a theoretical procedure.

When we adapted our mathematical theory to COMSOL, it permitted the normalization of the modes and allowed us to compute their excitation coefficients simply by evaluating a volume integral. This part was crucial, as it further resulted in a rapid and analytical method to calculate the electromagnetic field scattered by the resonator along with all the associated physical quantities, such as the scattering and absorption cross sections and the radiation diagram, as depicted in Figure 3.

Now that a method has been developed to understand how light is scattered by nanoresonators, we expect that this will assist in the spread of nanoresonators in a number of optical applications, ranging from sensors and defense applications to computers and electronics. A new breed of devices called nanoelectromechanical systems (NEMSs) will soon see the light, thanks to simulation. ◎

SIMULATION TURNS UP THE HEAT AND ENERGY EFFICIENCY AT WHIRLPOOL CORPORATION

Researchers at Whirlpool Corporation are using simulation to test innovative and sustainable technologies for new oven designs.

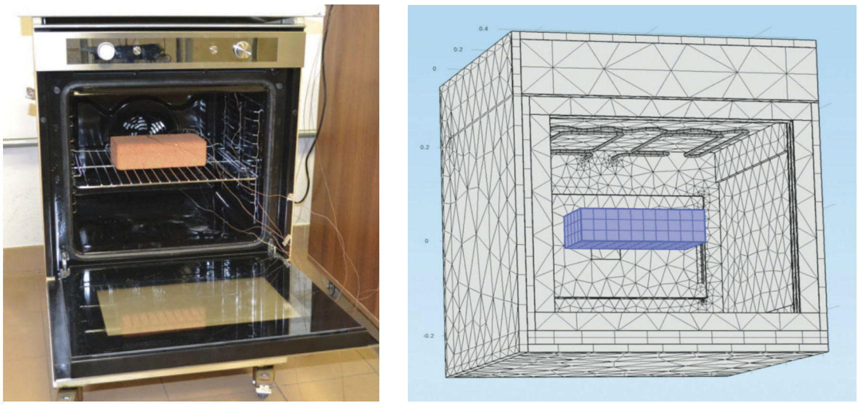


FIGURE 1: Left: Whirlpool's Minerva oven set up for the "brick test." Right: The meshed geometry.

By **ALEXANDRA FOLEY**

IN TERMS OF energy consumption, ovens have the most room for improvement of any appliance in the kitchen, with only 10 to 12 percent of the total energy expended used to heat the food being prepared. This is one of the reasons why Whirlpool Corporation, the world's largest home appliance manufacturer, is exploring new solutions for enhancing the resource efficiency of their domestic ovens. Using a combination of experimental testing and finite element analysis (FEA), Whirlpool engineers are seeking solutions to improve energy efficiency by exploring new options for materials, manufacturing, and thermal element design.

In partnership with the GREENKITCHEN project, a European initiative that supports the development of energy-efficient home appliances with reduced environmental impact, researchers at Whirlpool R&D (Italy) are studying the energy consumption of their ovens by exploring the heat transfer processes of convection, conduction, and radiation. "Multiphysics analysis allows us to better understand the heat transfer process that occurs within a domestic oven, as well as test innovative strategies for increasing energy efficiency," says Nelson Garcia-Polanco, Research and Thermal Engineer at Whirlpool R&D working on the GREENKITCHEN project. "Our goal is to reduce the energy consumption of Whirlpool's ovens by 20 percent." Even if only one electric oven is installed in every three households in Europe, the resulting increase in efficiency would reduce the annual electricity usage of European residential homes by around 850 terawatt-hours. This would lead to a reduction of about 50 million tons in CO_2 emissions per year.

» LIGHT AS A FEATHER, NOT THICK AS A BRICK

A LOAF OF bread should be as light as a feather, not, as they say, as thick as a brick. Ironically, the standard test for energy consumption in the European Union, known as the "brick test," involves heating a water-soaked brick and measuring temperature distribution and evaporation during the process. "A brick is used since it offers a standard test for all ovens. The brick is created to have similar thermal properties and porosity as that of many foods, making it a good substitute," says Garcia-Polanco.

During the experiment, a wet brick with an initial temperature of 5°C is placed in the oven's center and is heated until the brick reaches a previously defined "delta" temperature (in this case, 55°C). The temperature and amount of water evaporated from the brick are recorded throughout the experiment. Using simulation, Garcia-Polanco and the team created a model of Whirlpool's Minerva oven to explore its thermal performance during this test (see Figure 1).

» ACCURATE SIMULATIONS PROVIDE THE RIGHT SOLUTION IN LESS TIME

THE SECRET TO efficient cooking lies in the heat transfer rate, which describes the rate at which heat moves from one point to another. Inside an oven, food is heated by a combination of conduction, convec-

> *"Our goal is to reduce the energy consumption of Whirlpool's ovens by 20 percent."*
> —**NELSON GARCIA-POLANCO, RESEARCH AND THERMAL ENGINEER AT WHIRLPOOL R&D**

GREENKITCHEN is a European Union funded research project where Whirlpool R&D is a partner.

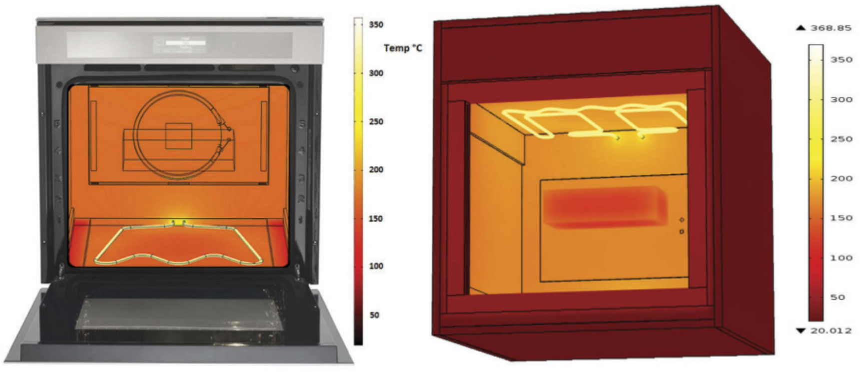
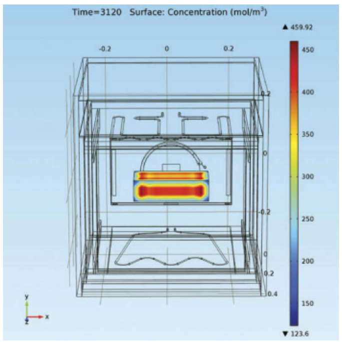


FIGURE 2: Predicted temperatures of the oven surfaces (color scale in °C) after 50 minutes in a broil cycle (right) and a bake cycle (left).



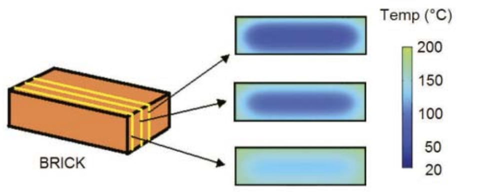


FIGURE 3: Left: Brick surface moisture concentration (in moles per cubic meter) at the end of the simulated test. Right: Predicted temperature profiles at different slices of the brick after 50 minutes at 200°C.

tion, and radiation. "The static cycle heats the oven from the bottom (bake) and the top of the cavity (broil) using the corresponding heating elements, while the forced convection cycle uses the same configuration along with an internal fan," says Garcia-Polanco. "Therefore, radiation is most important during a static cycle, and convection dominates during the forced convection cycle." The simulation took into account the different heat transfer rates of the various heating methods (see Figure 2) as well as a combination of different elements including material properties, oven shape, and the type of food being prepared.

There are several factors that proved especially important when considering the transient behavior of the oven model. "We considered the emissivity of the glass door, the thickness of the walls, and the material properties of the walls," says Garcia-Polanco. "We made a detailed comparison of the results of both the simulation and actual experiment throughout the heating cycle, which helped verify that our simulation was accurate."

From left to right: Joaquin Capablo, Energy Engineer; John Doyle, Principal Engineer, Energy & Environment; and Nelson Garcia-Polanco, Thermal Engineer.

In addition to predictions of the temperature of the oven surfaces, detailed information about the temperature profiles and moisture concentrations within the brick were acquired. "We looked at the temperature behavior within the brick," says Garcia-Polanco (see Figure 3). "When we compared data from our simulation with the experimental data, we found that our predictions about the internal temperature of the brick closely matched that of our experimental data." Knowing that the simulation is accurate will allow Whirlpool's team to probe the oven and brick at any point in space and time with confidence in the results they obtain. "For our future experiments, this knowledge will help us to save both time and money by reducing the number of prototypes and design iterations we go through before settling on a final oven design."

The team also looked at the water concentration in the brick throughout the experiment. The experimental results were very close to the simulation, with an average predicted value of 166 grams of evaporated water after 50 minutes and an actual value of 171 grams. "Knowing the rate at which water evaporates from the brick will help us to conduct further studies into different strategies for reducing energy consumption without decreasing the final quality of the product," says Garcia-Polanco.

» A RECIPE FOR HIGH-QUALITY, HIGH-EFFICIENCY COOKING

THE RESULTS FROM this verification study will help further the mission of GREENKITCHEN project to empower innovative households to reduce national energy consumption and improve energy efficiency in Europe. A proven, reliable model simplifies the verification of new design ideas and product alterations, helping designers to find the right solution in less time. "This study confirmed that our model is accurate, allowing us to be confident in the results when we test future design ideas," concludes Garcia-Polanco. "Our next steps will be to use this model to optimize the use of energy resources in the oven and to deliver a robust, energy-efficient design to the European market." ◎

INNOVATIVE PACKAGING DESIGN FOR ELECTRONICS IN EXTREME ENVIRONMENTS

Extreme environments and high currents pose challenges for designers in the power electronics industry. Using multiphysics simulation, Arkansas Power Electronics International has developed new packaging to improve the performance and thermal management of power electronics devices.

By **LEXI CARVER**

EVERY TIME YOU start your car, use your phone, or turn on a modern lamp, you're relying on a product from the power electronics industry. In addition to supplying products used by billions of people on a daily basis, this industry concerns itself with energy density, power density, customer safety, and cost per watt. Consequently, there is an obvious need for ways to analyze and refine designs for these devices while increasing efficiency and lowering cost.

» PUSHING LIMITS WHILE PREVENTING FAILURE

MECHANICAL, THERMAL, and electrical properties influence the performance and thermal management of power electronics devices; a temperature increase outside the specified operating conditions may cause failure or produce increased resistance, threshold drifts, and lower switching frequencies, all of which reduce efficiency and controllability. Parasitic inductances in device packaging create voltage spikes that shorten the lifetime of a device. Arkansas Power Electronics International, Inc. (APEI), a company that designs and manufactures high-efficiency power electronics, has addressed this problem by designing new packaging systems and power modules. Brice McPherson, a lead engineer at APEI, and his colleagues are developing power modules and discrete packages with better thermal management capabilities than the industry standard (see Figure 1). One of their designs has 25 percent reduced thermal resistance and half the inductance of the widely used transistor outline (TO) package.

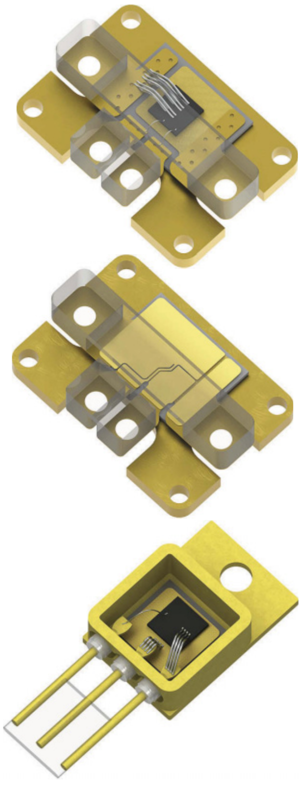


FIGURE 1: The custom SiC (top), custom GaN (middle), and TO (bottom) power modules.

Their goal is to create power modules with a packaging robust and flexible enough for use in many applications—one that is small and easy to configure, with good thermal conductivity and low inductance.

» SEMICONDUCTORS FOR EXTREME ENVIRONMENTS

A CLASS OF materials known as wide-bandgap semiconductors can operate stably at high temperatures and frequencies, and these materials therefore have an advantage over typical silicon-based power electronics. Systems based on wide-bandgap semiconductors may be more usable in extreme conditions—for example, in drilling equipment used at depths with higher pressures and temperatures than are currently reachable. It may even be possible to improve the survivability of equipment in environments as harsh as that on the surface of Venus.

Two materials have become the cornerstones for APEI's new designs: gallium nitride (GaN) and silicon carbide (SiC). For medium currents and thermal loads where extremely fast and efficient switching is required, GaN is optimal. For very high currents and thermal loading where large amounts of energy need to be processed in a small area—such as in a vehicular motor drive—SiC is the best choice. APEI worked with GaN Systems in Ottawa, Canada, a leading provider of high-performance GaN devices, to design the GaN power package. McPherson and his colleagues exploited the materials'

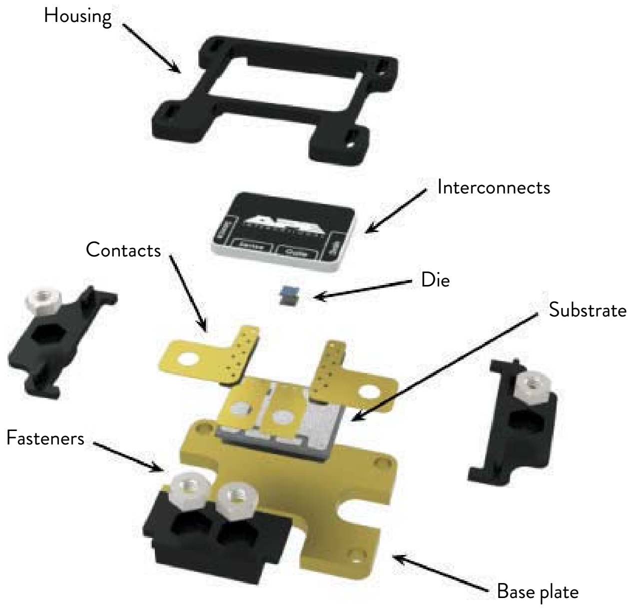


FIGURE 2: Power module components (above) and the assembled power module (bottom). Fully assembled, the entire device is a little larger than a quarter.

SiC Power Package	
Inductance	7.83 nH
Thermal Resistance	0.38°C/Watt
Operating Temp	225°C

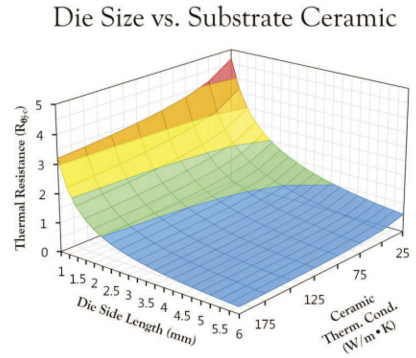


FIGURE 3: Parametric sweep showing how thermal resistance varies with changes in device size and thermal conductivity of the substrate.

properties to develop breakthrough power-packaging technology.

» *IMPROVING PERFORMANCE THROUGH REDUCED THERMAL RESISTANCE AND INDUCTANCE*

TO ACCOMPLISH THIS, they embarked on a search for the right combination of geometry and thermal and electrical properties to effectively optimize power density, weight, and switching frequency. They wanted a design that offered the ease of use and capabilities of a larger, higher-power module but was no larger than the TO option. Their new power module includes the die (the device), a copper base plate, contacts, interconnects, fasteners, a housing, and a metal substrate between the contacts and the base plate (see Figure 2).

McPherson combined his packaging and systems expertise with the simulation tools of COMSOL Multiphysics®. The LiveLink™ *for* SolidWorks® add-on let him directly import his geometry from SolidWorks® and run a parametric sweep analysis in COMSOL. He compared his designs, applied temperatures and voltage boundary conditions, and analyzed their electrical and thermal performances. He tested the effects of changing device dimensions, base plate thickness, substrate thickness, and material properties.

> *"It's very valuable to be able to simulate something before you invest money and time into prototyping and building it."*
>
> **—BRICE McPHERSON, LEAD ENGINEER, APEI**

One major benefit of the multiphysics modeling process was being able to model Joule heating and analyze the amount of heat generated in the conductors. "APEI specializes in high power density products, which need a lot of precise testing before they're perfected. It's very valuable to be able to simulate something before you invest money and time into prototyping and building it," McPherson says. The majority of the parametric sweeps he performed (one is shown in Figure 3) aimed to optimize thermal resistance, current-carrying capacity, and footprint.

"Designing for low thermal resistance involves selecting materials with high thermal conductivity, reducing the distance heat travels to leave the layers, and optimizing layer thickness to take advantage of thermal spreading," McPherson explains. "That's where parametric modeling is your best friend: You can set up parametric sweeps to find out exactly what's influencing

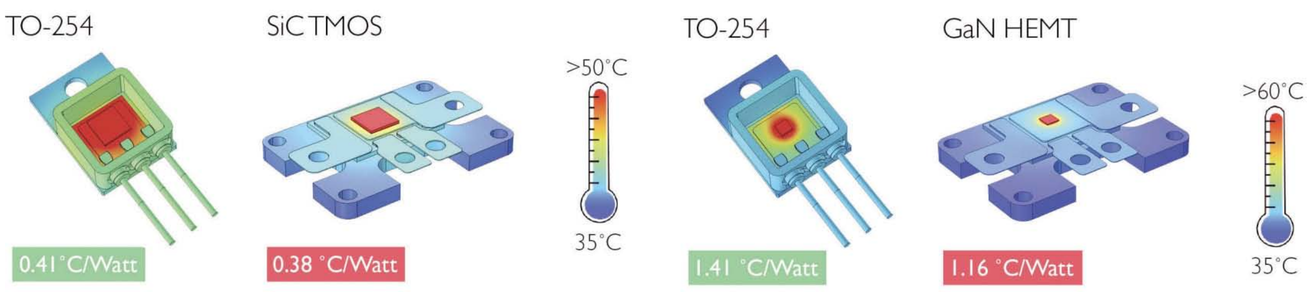


FIGURE 4: Thermal resistance results when comparing TO-254 to SiC (left) and TO-254 to GaN (right).

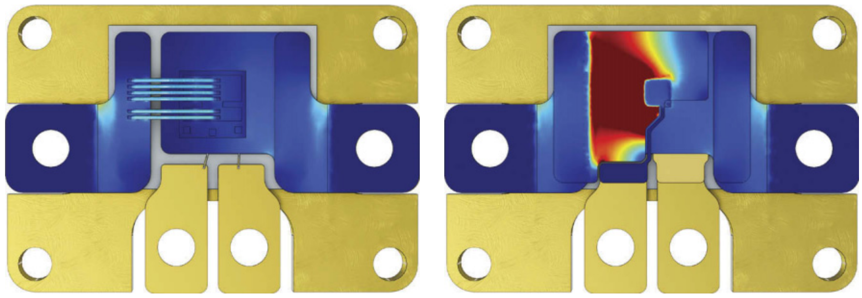


FIGURE 5: Current density gradients in the SiC (left) and GaN (right) geometries. In the SiC package, the current shows a relatively low density (preferred for higher currents), with the major concentrations found in the wire bonds. The GaN package has a higher average density, but more area available for conduction (ideal for low inductance).

the system the most and get the best compromise among performance, complexity, and cost." McPherson modeled a TO-254, a common TO transistor, to see how his designs (see Figure 4) compared.

Figure 5 gives a detailed view of current density in both packages. According to the simulations, APEI's power modules had lower thermal resistance than the TO-254 (see Figure 4). Even better, they both showed significantly lower inductance. The parameter with the greatest influence on the inductance turned out to be the device size, followed by the thickness of the base plate. To reduce inductance, it was critical to maximize the cross-sectional area of the device and minimize the current path length, while maintaining an acceptable thermal performance. The GaN module shows the least inductance, and the TO-254 exhibits the highest (12.98 nanohenries for the TO-254 vs. 7.5 nH and 7.83 nH for GaN and SiC, respectively). The current path length and conductor geometry drive the inductance trends, while the die size and material are less influential than in the thermal simulations.

APEI's new packaging is flexible enough to be used with either material, according to the needs of the customer. It operates well with GaN and SiC, which both allow for rapid, clean switching.

> *"You can set up parametric sweeps to find out exactly what's influencing the system the most and get the best compromise among performance, complexity, and cost."*
> —**BRICE McPHERSON**

APEI DELIVERS THE NEW PACKAGING STANDARD USING MULTIPHYSICS SIMULATION

MCPHERSON SUCCESSFULLY created a power module that improves on industry standards, with a packaging that ensures low inductance, good thermal management, and can be operated at temperatures over 225°C. His work demonstrates the potential of improving packaging to enhance current electronics technology and the use of a powerful simulation tool such as COMSOL to aid the design process. McPherson hopes that this design, with its strong thermal performance, will improve existing options but also open doors to new applications. His remarkable results are an encouraging move toward more efficient power modules, paving the way for power electronics to deliver higher currents and be used in more extreme conditions. Perhaps Venus is not so far away after all.

MAKING SMART MATERIALS SMARTER WITH MULTIPHYSICS SIMULATION

What if a material could be designed to transform in response to external stimuli, exhibiting certain characteristics only when exposed to a specific environment?

By **ALEXANDRA FOLEY**

MATERIALS THAT DEMONSTRATE different responses to varying external stimuli are known as "smart materials," and their discovery has led to the creation of products that perform on a whole new level. These engineered materials are developed to perform smarter and more efficiently than their predecessors, allowing materials to be designed based on the products and environments in which they will be used. Magnetostrictive materials are engineered smart materials that change shape when exposed to a magnetic field and they have proven crucial for the production of transducers, sensors, and other high-powered electrical devices.

Engineers at ETREMA Products, Inc. design devices using magnetostrictive materials for defense and other industry applications including sensors, loudspeakers, actuators, SONAR, and energy harvesting devices. The unique properties of magnetostrictive materials—their ability to mechanically respond to magnetic fields and their characteristic nonlinearity—make designing these devices a challenge.

Researchers at ETREMA have found that multiphysics simulation can be used to accurately represent the material properties and complex physics interactions within such devices, facilitating the production of the next generation of smart products.

» DESIGN AND SIMULATION OF MAGNETOSTRICTIVE TRANSDUCERS

MAGNETOSTRICTION OCCURS AT the magnetic domain level as magnetic regions realign in response to variation in either magnetic or mechanical energy, causing a change in a material's shape or magnetic state (see Figure 1).

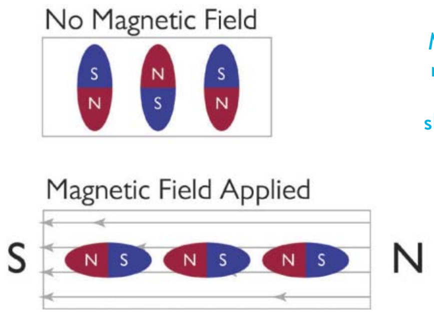


FIGURE 1: Magnetostrictive materials change their physical shape in response to an applied magnetic field and vice versa.

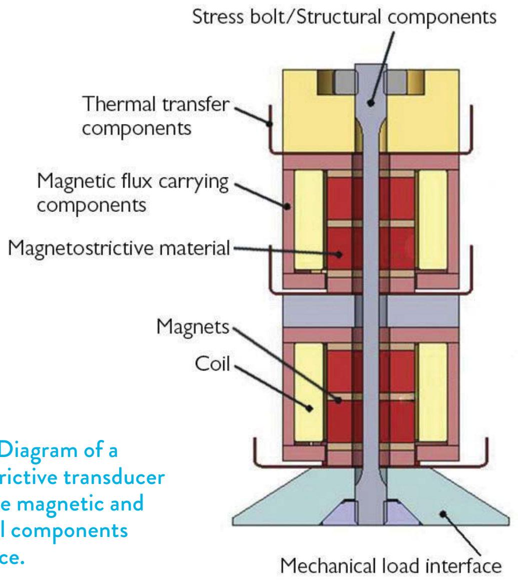


FIGURE 2: Diagram of a magnetostrictive transducer showing the magnetic and mechanical components of the device.

For example, the magnetostrictive material iron elongates by 0.002 percent when exposed to a strong magnetic field, and nickel contracts by 0.007 percent under that same field. Terfenol-D, a "giant magnetostrictive material," demonstrates deformations 100 times that of iron and was first developed by the U.S. Navy in the 1970s. ETREMA is currently its sole commercial producer.

ETREMA designs magnetostrictive transducers (see Figure 2) using Terfenol-D—devices that convert magnetic energy into mechanical energy and that are critical components of many larger, more complex systems. To accurately model these complex devices, ETREMA uses COMSOL Multiphysics® . Their simulations include permanent magnets and coils, the magnetic fields created by these coils, stress and modal analyses of structural mechanics components, as well as heat transfer in the device to mitigate heat generated by eddy currents and hysteresis. Fully coupled models are used to evaluate the overall electro-mechanical characteristics of these transducers.

"When we first began to expand our engineering process to model such devices, our modeling techniques consisted of a system of disjointed methods that included hand calculations, equivalent circuits, and single-physics modeling," says Julie Slaughter, Senior Engineer at ETREMA. "However, our decision to move toward a devices and systems approach coincided with the advent of multiphysics finite element analysis and we adopted COMSOL as our modeling tool for systems-based modeling. This greatly improved our understanding of transducers and their design."

ETREMA's modeling approach demonstrates the unique flexibility of COMSOL Multiphysics. First, models are created to analyze individual physics; then, multiphysics simulations are built to determine how the physics interact with one another. This approach allows for both a targeted look as well as a complete picture of the physics interactions taking place within their devices.

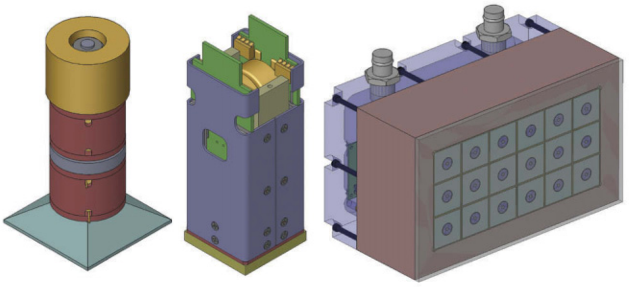


FIGURE 3: Closely packed SONAR array, which includes a magnetostrictive transducer at its core. From left to right: a single magnetostrictive SONAR transducer; the transducer packaged with power electronics; and the full array, made up of 18 transducer elements.

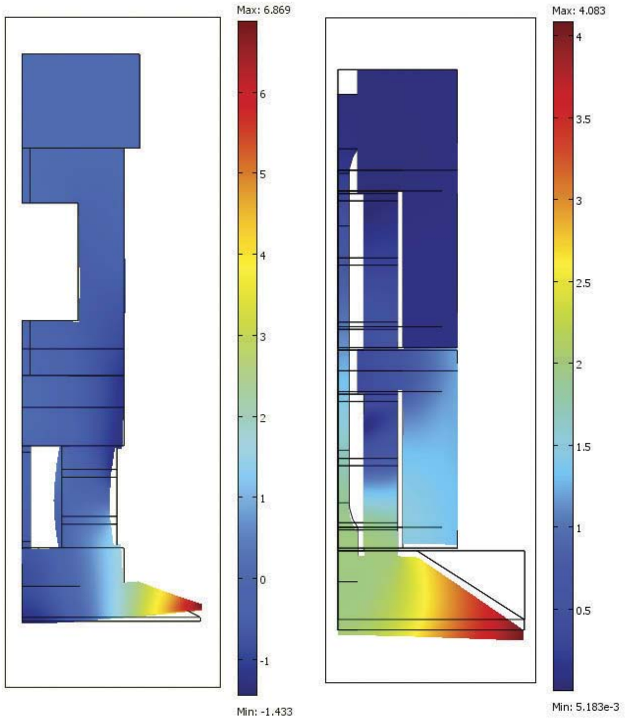


FIGURE 4: Left: The initial transducer design shows severe bending in the mechanical interface to the load. Right: The redesigned model demonstrates reduced deformation.

» DESIGN DIAGNOSIS

AN OVERVIEW OF this design process can be seen in the design of a close-packed SONAR source array, which includes a magnetostrictive transducer at its core (see Figure 3). Not only are there many different material properties that need to be analyzed and optimized, but the transducer also contains a combination of electrical, magnetic, and structural physics that interact within the device.

Deformation within the transducer was analyzed using a single-physics model in which static loads were used to estimate fatigue and determine if the prestressed bolts and Terfenol-D core would hold up against the system's strain. The initial transducer design demonstrated severe bending at the mechanical interface between the transducer and the load, however further load analysis and structural optimizations allowed the transducer to be redesigned with reduced deformation and stress (see Figure 4). The model was also used to detect undesirable modes of vibration in the operating bandwidth that could affect overall performance.

Single-physics models were developed to evaluate the DC and AC magnetics separately. "We matched the electrical requirements of the transducer with the available power amplifiers, and evaluated electrical losses due to eddy currents and air gaps within the device," says Slaughter. Permanent magnets were integrated into the transducer design to magnetically bias the material to enable bidirectional motion and minimize nonlinear behavior and frequency-doubling effects. "Stray magnetic fields in close proximity with the electron-

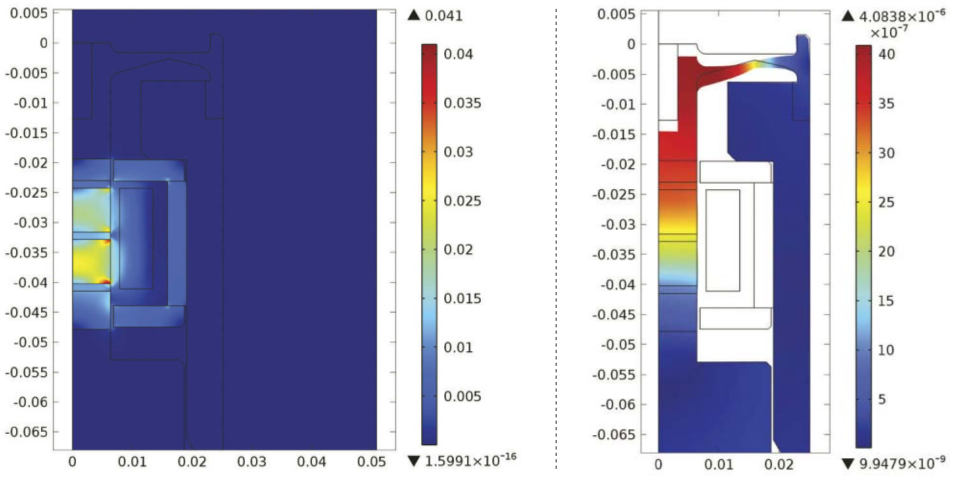


FIGURE 5: Magnetic fields generated from a 1-ampere input to the coil. Displacements are calculated using the maximum current input.

ics can cause problems with noise and corrupted signals," Slaughter explains. "We had to carefully consider the design of the transducer's magnetic circuit as well as the placement of key electrical components to avoid stray magnetic flux that can interfere with the electronics."

Using COMSOL, ETREMA researchers were able to find a design that was optimized for the competing requirements of both the AC and DC magnetics. The models for this design demonstrated that the magnetic fields mainly stay confined to the magnetic components, thereby reducing the exposure of the electronics to the magnetic fields.

"When setting up our multiphysics models, we use coupled equations, where strain is a function of stress and also of the magnetic field."

—JULIE SLAUGHTER, SENIOR ENGINEER, ETREMA PRODUCTS, INC.

» DESIGN VALIDATION

THE NEXT STEP in ETREMA's design process was to create fully coupled multiphysics models. "When setting up our multiphysics models, we use coupled equations, where strain is a function of stress and also of the magnetic field," says Slaughter. "This is the basis of implementing coupled magnetostriction in COMSOL." Using this process, Slaughter and her team determined how the magnetic and mechanical domains would interact within the device and ultimately predicted how the magnetostrictive material would behave (see Figure 5).

"For the coupled linear magnetostrictive model, our simulations showed that the device would perform largely as expected, with few adjustments needed in either the mechanical or magnetic aspects of the design," she continues. "The magnetic fields remained confined to the magnetic circuit, and deformations remained minimal."

These multiphysics models were further validated using experimental data. "The models of impedance and displacement were very similar to experimental results," says Slaughter.

» A MULTIPHYSICS APPROACH TO MODELING

AT ETREMA, BOTH single-physics models and fully coupled multiphysics simulations have proven to be powerful tools for transducer design, evaluation, and optimization. The construction of single-physics models allows for design diagnosis prior to the development of multiphysics models, where attributing an undesired interaction to a certain physics type is more straightforward. Coupled models then further describe the way the individual physics will interact in the real world. Although ETREMA focuses on magnetostrictive materials, all transducer technologies involve coupled multiphysics interactions, including piezoelectric, electrostatic, and electromagnetic effects, and each can benefit from the use of multiphysics simulations. Finite element models can be used at different stages of product development: During design development, for the evaluation of existing products, and when it is necessary to troubleshoot performance issues. ◎

FROM CONCEPT TO MARKET: SIMULATION NARROWS THE ODDS IN PRODUCT INNOVATION

By **CHRIS BROWN**

IN TODAY'S ELECTRONICS industry, innovation is essential for growth, while a short time from idea to market is the key to realizing maximum value. The argument that huge gains are possible by improving decision-making processes at an early stage of R&D—known for good reason as the "fuzzy front end"—is undoubtedly sound. In my experience, however, it is the quality of an idea and, crucially, the quality of the evidence supporting that idea that can really make the difference. Even the best processes cannot produce decisive outcomes when dealing with potentially ground-breaking technologies backed up by scant evidence. A quick, cost-effective way of narrowing the odds is needed.

Sharp Laboratories of Europe (SLE) in Oxford, UK is part of a global network of Sharp R&D sites responsible for delivering new technologies to the corporation. Our role is not only to support the continuous improvement of Sharp's current product portfolio but to secure the future success of Sharp in the longer term through more radical innovation to create entirely new product lineups.

A distinct change in the lab since I joined SLE almost 15 years ago is the move to a more multidisciplinary way of working. There has been a shift in focus to systems or products as a whole, such as health systems and energy systems. The multidisciplinary nature of our work brings with it an increased complexity, as our researchers must understand how all the parts fit together and the complicated relationships that exist at the boundary between two physical systems.

Fortunately, as the complexity of the problems we face in the lab has increased, advances in computer modeling provide a helping hand in the form of powerful finite element simulation tools such as COMSOL Multiphysics®. For us, a key advantage of COMSOL is that it enables virtual experiments to be carried out that cross the boundaries of different physical mechanisms and that would be difficult, time-consuming, and costly to try out in the real world.

One example of where COMSOL has been a valuable tool is in our project to develop a lab-on-a-chip device for medical diagnostic applications. The project leverages Sharp's LCD manufacturing expertise and is based on a technology, known as digital microfluidics, that enables precise control and manipulation of sub-millimeter-scale fluid droplets on top of an electronic sensor array. A key challenge in the development of the device lay in designing the fluid input ports to allow biological fluids and test reagents to flow onto the array under electronic control. Critically, the multiphysics capability of COMSOL enabled us to model interactions between the solid-liquid interface, electric field distribution, and fluid flow simultaneously. The result was an initial design for a fluid input structure that provided a more accurate starting point for experimental work when compared with simple hand calculations. The consequent reduction in the number of physical design iterations helped us reduce the R&D prototyping time and cost and will help bring the device to market more quickly than could otherwise have been achieved.

As electronics continue to proliferate into yet more facets of modern life, the boundaries between what were once distinct scientific and engineering disciplines will become ever more blurred. In research organizations such as SLE, where scientists and engineers are faced with increasingly complex problems and where speed of development is increasingly vital, COMSOL Multiphysics is well placed to become a truly indispensable tool. Those of us working in the fuzziness appreciate the guiding hand it provides. ◎

CHRIS BROWN *is manager of the Health & Medical Devices group at Sharp Laboratories of Europe. He holds B.A. and M.Eng. degrees in Electrical and Information Sciences from Cambridge University. After spending 10 years developing display technology for Sharp, including three years in Japan, he now leads a multidisciplinary research initiative combining electronics and biology to create new devices for the health care market. He is glad he can still find the time to work with COMSOL.*

The Next 50 Years

THE FUTURE WE DESERVE

A SPECIAL REPORT

1964, THE YEAR OF *IEEE SPECTRUM*'S FOUNDING AND OF THE NEW YORK World's Fair, was a time of bold and futuristic thinking. Visionaries then predicted that the world of 2014 would be shaped by remarkable technological triumphs. And indeed it is. ● But hardly any of them are the ones that were forecast in 1964. ● So, for this 50th anniversary issue, we've described what we *hope* will be achieved in coming decades, rather than guess what will probably be achieved. We've put together desirable scenarios for eight of the most promising of today's technologies. To broaden the perspective, we've also considered what could go wrong and included a bracing new work of science fiction, written for this issue by Nancy Kress. ● Though we didn't set out to predict what life will be like a half century from now, we do think we can do better than our peers did in 1964. Some of the key technologies then—integrated electronics, nuclear power, space vehicles, and optoelectronics—were very new in 1964 and therefore hard to visualize decades out. ● It was kind of like looking at a toddler and trying to see the future adult. We, at least, have the advantage of looking at an adolescent, with that mix of vulnerability, confidence, restlessness, and exuberance. ▶

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

BIONIC

THE FUTURE WE DESERVE

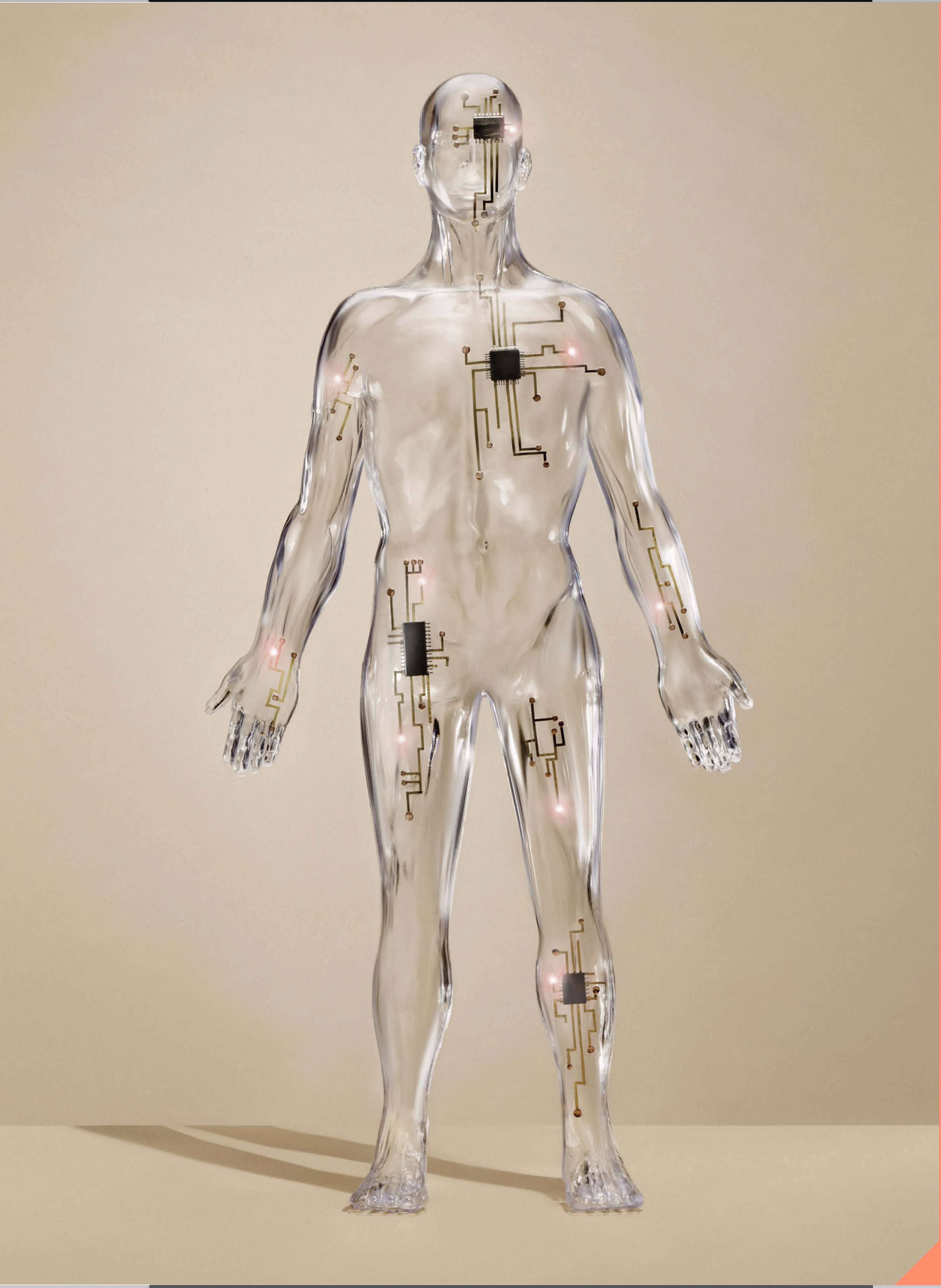
THE END OF DISABILITY

Prosthetics and neural interfaces will do away with biology's failings

By Eliza Strickland

HUGH HERR IS A LIVING EXEMPLAR OF THE MAXIM THAT the best way to predict the future is to invent it. At the age of 17, Herr was already an accomplished mountaineer, but during an ice-climbing expedition he lost his way in a blizzard and was stranded on a mountainside for three days. By the time rescuers found him, both of his legs were doomed by frostbite and had to be amputated below the knee. Once his scars healed, Herr spent months in rehab rooms trying out prosthetic legs, but he found them unacceptable: How could he climb with such clunky things? Surely, he thought, medical technologists could build replacement parts that wouldn't slow him down. • Today, three decades after his accident, Herr walks on bionic limbs of his own creation. As director of the biomechatronics group at the MIT Media Lab, Herr developed advanced

PHOTOGRAPH BY Adam Voorhes



IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

prosthetics that he uses to walk, run, and even rock climb. And now, as he works with his colleagues to establish MIT's new Center for Extreme Bionics, Herr is setting out not just to reinvent himself but the whole of society. "Fifty years out, I think we will have largely eliminated disability," he declares, adding that he's referring not just to physical disabilities but to many emotional and intellectual infirmities as well.

Herr believes the solutions lie not in biological or pharmacological cures but in novel electromechanical additions to our bodies. He gestures to his own artificial limbs to make the point. "My legs weren't grown back; I wasn't given a total limb transplant," he notes. "If you eliminate the synthetics, all I can do is crawl. But with them," he says with a slow smile, "I can more or less do anything."

The MIT scientists are part of a movement aimed at ushering medicine into a cyborg age. All over the world, engineers are building electronics-based systems that communicate directly with the human nervous system, promising radically new treatments for a variety of ailments and conditions, both physical and mental. While Herr's team focuses on giving people better control of their prosthetic limbs, other researchers are trying to give patients better control of their emotions. One promising experiment targets depression with deep brain stimulation (DBS), in which electrodes implanted in the brain send steady pulses of electricity to certain problematic neural areas. Others are developing gear to compensate for intellectual deficits, such as a California project to build a memory-augmenting prosthetic.

In all of these projects, researchers started with the notion that a surprising range of afflictions can be most effectively treated by learning the electrical language that the brain uses to govern our movements, moods, and memories. By 2064, it's entirely possible that neural engineers may be fluent enough to mimic those instructions, allowing them to repair a human being's faulty systems by rewiring them.

THE BODY IS ELECTRIC. WE'VE KNOWN that since the 18th century, when Luigi Galvani touched a charged scalpel to a nerve and made a dead frog's leg kick. Neurons in the brain send out pulses of voltage when they "fire," and the patterns of their pulses make up our sensations, our musings, and our actions. The electric signals generated in the brain also travel through the spinal cord and along the peripheral nerves to instruct the body's muscles and organs. Medicine in the 20th century relied primarily on pharmaceuticals that could chemically alter the action of neurons or other cells in the body, but 21st-century health care may be defined more by electroceuticals: novel treatments that will use pulses of electricity to regulate the activity of neurons, or devices that interface directly with our nerves.

> **"Fifty years out, I think we will have largely eliminated disability"**

Herr's lab focuses on advanced prosthetic legs, and it is developing systems that will allow amputees to control a titanium-and-plastic limb as naturally as they would a flesh-and-blood leg. The goal is to record and understand the brain's commands and then to send those instructions to the prosthetic. Herr has already tested an early version of such an integrated device. In that setup, he flexed the muscles around his knee as if he were taking a step; then an electromyograph captured the electric signal in those muscles and translated it into a digital signal that made sense to the microprocessors in his artificial foot. Just like that, he stepped.

Even more direct connection between brain and machine will be possible, Herr says, when he succeeds in connecting prosthetics directly to the peripheral nerves in amputees' residual limbs. Not only could such a system relay more precise commands to the prosthetic, it could also send sensory information back up the nerves. And when amputees actually feel the grass beneath their prosthetic toes, Herr says, it will change the way humans view this technology. "When that happens it will not matter what [the prosthetic] is made of, it will be you," he says. "I feel, therefore I am."

PEOPLE WITH BODILY DISABILITIES typically have a moment that marked the onset of their troubles—for example, Hugh Herr's ill-fated climbing excursion. In contrast, people with the crushing emotional difficulty of depression often don't know when it started, nor do they necessarily define themselves as disabled. Depression is just the state of mind they live with daily, stripping the present of all pleasure and the future of all hope.

Neuroscientists discovered years ago that this existential dread can be treated

NO ACHILLES' HEELS: Aimee Mullins and Hugh Herr foresee a day when upgrading a body is routine. Mullins, an actress and advocate for advanced prosthetics, was the first double amputee to compete at the highest levels of U.S. collegiate track-and-field events.

PREVIOUS PAGE: PROP STYLIST: ROBIN FINLAY; THIS PAGE: JILL GREENBERG/CORBIS OUTLINE

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

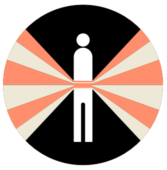
by using electricity to alter the activity of neurons, and they are now putting that knowledge to use. DBS, one of the most exciting experimental treatments for depression, uses an implanted "brain pacemaker" that sends steady pulses of electricity to certain brain regions. It's a technology that was pioneered to stop Parkinson's patients' tremors, but it's now being explored for a dizzying array of neural and psychiatric disorders, including depression, obsessive-compulsive disorder, and PTSD. "Right now we're at the beta testing stage of DBS for psychiatry," says Helen Mayberg, a neurology professor at Emory University and an authority on DBS for depression.

More than 100 000 Parkinson's patients have had electrodes implanted in the motor control regions of their brains, where the stimulator's pulses reduce the activity of neurons that are misfiring. But for disorders like depression, both the target for treatment and the mechanism of action are considerably less clear. "The limiting factor is actually the neuroscience, not the engineering," Mayberg says. She used brain imaging studies to pinpoint a particular region, Brodmann area 25, as overactive in depressed patients, and she has implanted the DBS device in this region of the brains of about two dozen patients who haven't responded to a slew of medications and therapies.

These test subjects are desperate, so overwhelmed by depression that they're willing to undergo experimental brain surgery. And the results have been remarkable. While antidepressant medications typically take weeks to kick in, many patients in the DBS experiments have reported a shift in mood instantly–literally the moment that the device is turned on. One patient reported an immediate sense of social connection; another expressed a desire to go bowling, a pastime she hadn't enjoyed for years. Most patients have chosen to keep their DBS systems activated after the formal experiments ended, and Mayberg says she's seen ample evidence that their improved lives can't be chalked up to a placebo effect. "When my patients' batteries die, they know it," she says.

Despite the dramatic results in DBS depression treatment, there was a setback in the field last year when a major clinical trial was halted. The device manufacturer, St. Jude Medical, announced that the trial it had funded failed a "futility analysis," but it hasn't explained exactly what went wrong. Mayberg notes that there are many variables that can influence the effectiveness of DBS; for example, even if the trial had targeted the correct region, the timing of the pulses may have been off. St. Jude may have rushed ahead too quickly, she says, trying to create a commercial product before the basic science of how such devices work is truly understood.

Bespoke Medicine



While engineering will play a central role in 21st-century medicine, biological treatments will hardly vanish. Those treatments will be shaped by the coming ubiquity of cheap genome sequencing, which will enable a new model of personalized genetic medicine. The change will start in the maternity ward, where newborns in their bassinets will receive full genome scans, resulting in complete printouts of their genetic vulnerabilities. Then, as those babies grow up and proceed through life, their physicians can design custom-made health-care regimens to ward off trouble and can prescribe the medications that their bodies will respond to best. Today the cost of a genome scan is nearing US $1000, and the scans are becoming common in cancer hospitals. When the price drops to $100, they'll be common everywhere. *—E.S.*

The good news for all would-be brain engineers is that massive neuroscience initiatives have recently been launched in the United States and Europe. The BRAIN Initiative, announced by U.S. president Barack Obama in 2013, will dedicate hundreds of millions of dollars to developing new tools that can better record and analyze brain activity. In Europe, meanwhile, the Human Brain Project is using supercomputers to simulate a complete human brain so as to better understand how it functions. It's very possible that in 50 years, DBS and other electrical techniques will be part of mainstream psychiatry, Mayberg says. But that will require scientists to know as much about the workings of a neuron as engineers do about the workings of an electrode.

ONCE PHYSICAL AND EMOTIONAL DISabilities have been conquered, the intellectual failures associated with aging will be a natural next target, says Theodore Berger, a professor of biomedical engineering at the University of Southern California. In fact, by 2064, going cyborg may simply be the sensible and economical thing to do. "We're living longer, so aging problems, and cognitive problems in particular, are going to be more and more prevalent," Berger says. "The cost of a cognitive prosthetic will pale in comparison to taking care of a person with dementia for 20 years."

It's quite possible that Alzheimer's patients of the future will be equipped with memory prosthetics derived from the devices being invented in Berger's lab today. His work began with delicate electrodes inserted into a rat's hippocampus, the brain structure responsible for encoding memory. Berger first deciphered the relationship between the input signals from neurons that process a brief learn-

ILLUSTRATION BY Greg Mably

[redacted]

ing experience–for example, which lever a rat should press to gain a sip of sugar water–and the output signals from neurons that send the information on to be stored as a memory.

Once he had mapped the correlations between the two electrical patterns, Berger could record an input signal and predict the output signal–in other words, the memory. He didn't need to know which part of the input pattern coded for the dimensions of the lever or for the taste of the sweet reward. He simply mathematically generated the output signal and sent it to the memory-storage neurons. "It's like translating Russian to Chinese when you don't know either language," Berger says. "We don't want to know either language; we just want to know how this pattern becomes that pattern."

Berger proved that he could implant the memory of the lever-and-reward test in a rat with a damaged hippocampus that was unable to form memories on its own. Even more remarkable, he implanted the memory in a rat that had never before undergone the test or seen the levers. The rat entered the test chamber for the first time, pressed the correct lever, and sucked down the sweet nectar.

With the knowledge of how to record and store memories, Berger can imagine a prosthetic device that encodes memories on a chip. He and his colleagues have already advanced to primate experiments, and he expects to proceed to the first human trials in the coming years. "It will absolutely happen," he says. In 50 years, he says, elderly people could have devices that they switch on to remember something as trivial as where they put their car keys or as meaningful as their grandchildren's names.

Berger optimistically believes his technology will be embraced, but it's easy to imagine a backlash against such synthetic additions to our fleshy bodies. Back at MIT, Hugh Herr says he's heard from plenty of people who are frightened by his predictions of physical, emotional, and intellectual augmentations. He echoes their typical refrain: "Will we change humans so much that they cease to be human?" But Herr believes that such philosophical questions will fall by the wayside as broad swaths of patients begin to benefit from their machined parts. He imagines a world in which amputees gain freedom, depressed people find joy, and the elderly hold on to their life stories. "People are suffering horribly now," Herr says, "and that's going to end." ■

WHAT COULD POSSIBLY GO WRONG?

Cyborg Castes

Biomedical enhancements could lock in inequality

No one who works on the biomedical frontier believes that humans will be content with using advanced prosthetics and brain implants only for repair. Once these technologies have been proven safe and reliable for people with disabilities, some people with unimpaired bodies will start clamoring to use them as technological augmentations.

MIT's Hugh Herr imagines that synthetic body parts could easily become more desirable than biological parts, especially as people age. "You wake up at the age of 50 and your joints are stiff, but your friend has bionic limbs that he upgrades every year that make him feel like an 18-year-old," Herr says. "What would you do?"

Meanwhile, Theodore Berger at the University of Southern California has already tried his memory prosthetics on rats that have no cognitive deficits. He found that he could dramatically boost the rats' performance on memory tasks. When the prosthetics were activated, "it was remarkable how much better they did," he says.

Such physical and cognitive enhancements could benefit individual humans but take a terrible toll on humanity as a whole, argues Nicholas Agar. An associate professor of philosophy at Victoria University of Wellington, in New Zealand, Agar is the author of several books that are critical of radical human enhancement. "When you introduce these technologies into a society where there are vast inequalities of wealth, what's the effect of that?" he asks.

Augmenting technologies might seem like a novel form of cosmetic surgery at first, just another way for wealthy people to boost their egos or improve their quality of life. But cognitive enhancements in particular could quickly create an elite class of cyborgs who go to the best schools, get the best jobs, and run the world. Agar worries that the divisions between the haves and have-nots would eventually be locked in by reproductive isolation. "What are the dating prospects between someone who has access to cognitive enhancements and someone who hasn't?" he asks. —*E.S.*

POST YOUR COMMENTS at http://spectrum.ieee.org/biomed0614

ILLUSTRATION BY **MCKIBILLO**

SPACE

THE FUTURE WE DESERVE

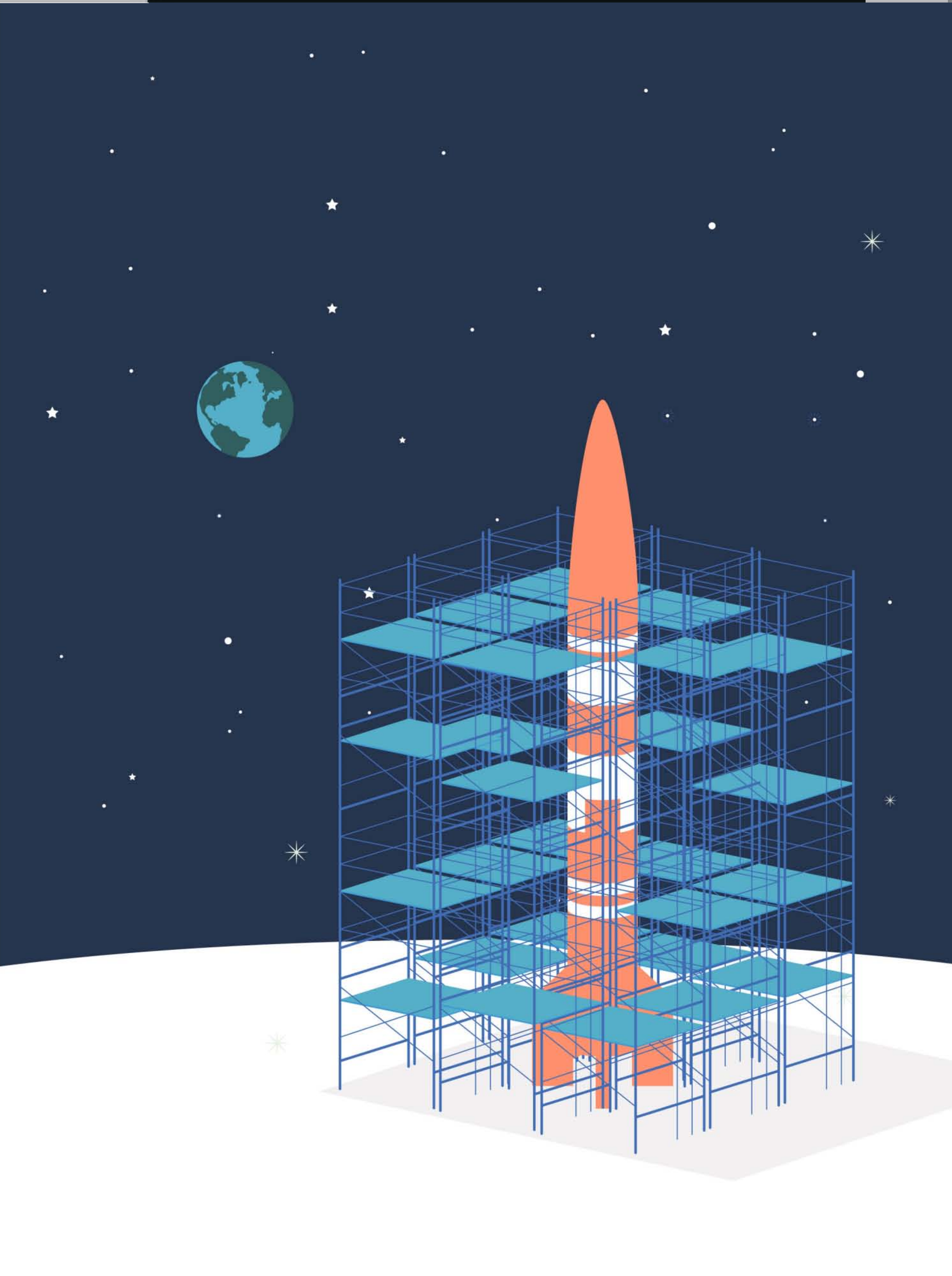
FEWER LAUNCHES, MORE SPACE

Technologies that exploit space resources will finally open up the solar system

By Rachel Courtland

THE FIRST ROBOT CAPABLE OF BUILDING ANYTHING, including a replica of itself, might cost a fortune to develop; the billionth copy would be as cheap as dirt. Send some of them into space and they could build new armies out of planetary rubble and dust, then go on to construct enough spaceships and refueling stations to carry the human race to other planets and, eventually, other stars. • That's the scenario laid out some 25 years ago by a team of academics and NASA engineers meeting at the University of Santa Clara, in California. They envisioned robotic factories that would cover the moon and exploit the asteroid belt, extracting the resources needed to build more and better versions of themselves and also vast orbiting telescopes, space colonies, and other structures too big to launch from Earth. Over time, the

ILLUSTRATION BY Ben Wiseman



THE FUTURE WE DESERVE

researchers wrote, these bots could "produce an ever-widening habitat for man throughout the Solar System" and beyond it. The approach could become so successful, they warned, that we might have to worry about robotic population control.

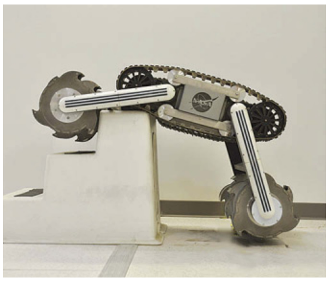
None of that, of course, has come to pass. Except for solar power, everything we use in space comes from Earth. But signs of change might be on the horizon. The next few years will see the launch of the first equipment that can make water out of lunar soil and print entirely new structures in microgravity. These are the seeds of the two basic technological capabilities–resource extraction and structure fabrication–that will be needed to build things in space that don't have to be launched from Earth.

If these technologies mature, experts say, they could transform the space environment. In 50 years, commercial outfits may tow drinking water, extracted from icy asteroids, to thirsty astronauts in Earth orbit. Vast solar arrays, built on trusses made from cemented lunar soil, could beam energy to Earth's surface. Radio antennas hundreds of meters wide could scrutinize the black hole at the center of the galaxy. And humans could finally be able to gather the resources they need for round-trip journeys to the surface of Mars.

NOTHING ABOUT THIS FUTURE IS guaranteed. Space plans shift with the political winds, and there is perennial debate over why we should go to space and what the balance of human and robotic exploration should be.

But robotic systems capable of construction and resource utilization could address the single biggest obstacle to the exploration of space: the expense.

"The technical facts of life in space are that it's hard to get there, it's hard to stay there, and it costs money to do it repeatedly," says Paul Spudis, a scientist at the Lunar and Planetary Institute, in Houston. Rocket companies still charge roughly US $10 000 to $20 000 to loft every kilogram of stuff into low Earth orbit. Many are now eying newcomer SpaceX, which is promising to deliver lower prices with a new heavy-lift rocket. But driving down the costs significantly would require either many more launches, to achieve economies of scale, or an improvement on chemical rocketry. Neither is on the horizon, Spudis says, and that leaves us with one alternative. To get beyond low Earth orbit and the half dozen lunar landings already under our belts, we must find a way to live off the land.



MINE AND MAKE: A version of NASA's RASSOR robot [top] might one day excavate lunar soil and ice. Later this year, Made in Space's 3-D printer [bottom] will be installed on the International Space Station.

TOP: NASA; BOTTOM: MADE IN SPACE

The moon alone has plenty of raw material to go around. The loose soil can be sintered or glued together to make crude structures. Silicon, which makes up roughly 20 percent of the soil by weight, can be extracted and purified to create rudimentary solar cells. And, crucially, there seems to be water, a multipurpose resource that can be purified for drinking, poured into containers to make radiation shielding, and split into hydrogen and oxygen to form rocket fuel. The ice locked up in the moon's north pole alone, Spudis says, is "enough to launch the equivalent of a space shuttle from the surface of the moon every day for 2200 years."

We could do far more in space if we make what we need out of what we can find, says Mason Peck, a professor of mechanical and aerospace engineering at Cornell and former NASA chief technologist. "I like to say that all the mass we're ever going to need to explore in space is already in orbit. It's just in the wrong shape."

GETTING MASS INTO THE RIGHT SHAPE is one of the goals of NASA's Swamp Works. The laboratory, based at Kennedy Space Center, in Merritt Island, Fla., occupies a building where Apollo astronauts once trained; it now boasts perhaps the world's largest collection of "lunar simulant"–artificial moon dirt. Some 120 tons of the stuff, detritus of a mining operation in Black Point, Ariz., sit in a glass-walled room. Here physicist Philip Metzger and his colleagues test the Regolith Advanced Surface Systems Operations Robot, or RASSOR, a rugged-looking industrial rover the size of a bumper car. RASSOR is more or less rectangular when stretched out. At each end, a pair of pivoting arms holds a long, hollow, rotating drum, studded with shovel-shaped openings. For digging leverage against the moon's reduced gravity, these drums are rotated in opposite directions, collecting lunar soil as they spin. When full, the robot can drive to a processing station, fold up so as to place a drum above a collection spot, and rotate the drum in reverse to empty it.

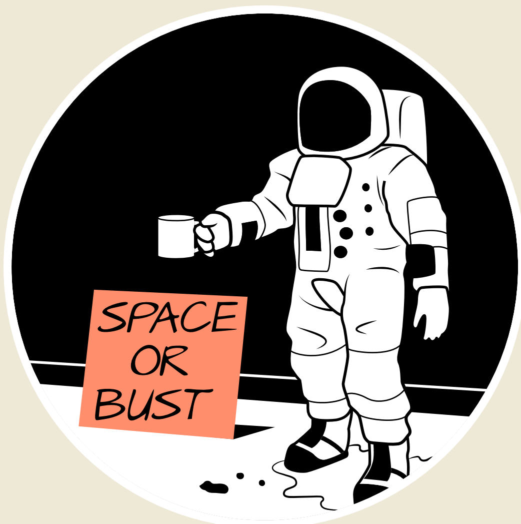
Metzger expects that such technology could kick off a lunar industry that slowly bootstraps its way up in sophistication. Crude robotic factories, remotely operated by humans, would be used to build slightly more capable systems, which would make even more capable ones, and so on. Metzger and his colleagues have modeled how this might work, and they reckon that as little as 12 metric tons of equipment sent to the moon would be enough to jump-start the evolution of a self-sustaining robotic industry. In time, he says, this approach could lead to the robotic colonization, or "robolonization," of the solar system.

This might sound outlandish, Metzger says, but most of what we build in space doesn't have to be as sophisticated as what we send from Earth. Because launch mass isn't a concern, he says, "we can build a giant, clunky robot out of iron instead of a small, lightweight one out of titanium." Truly advanced components, such as computer chips, could be shipped in batches and slotted into robots until they too could be manufactured in space. One of the key challenges, Metzger says, will be improving reliability. Lunar dust has a habit of getting into everything, and regular human repair missions can't be expected.

RASSOR is not slated for launch, but another NASA team is preparing a flight-ready version of what could become the first equipment to extract and make resources on the moon: the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) experiment. RESOLVE is currently an experiment without a spacecraft, but NASA hopes to find a way to launch it on a rover as early as 2019. It is designed to hunt for hydrogen, which could possibly point the way to water ice. While in operation, RESOLVE will also attempt to make water, by heating lunar soil to 900 °C to release oxygen and combining it with hydrogen carried in from Earth.

For any harnessing of space resources to work, many experts say, the government will need to play a big role, creating infrastructure much as it might build a mail system or a network of highways or any other backbone of commerce. But that hasn't stopped private companies from wading in. One of these is Planetary Resources, which is setting its sights on trips to near-Earth objects beginning in the early 2020s. On its first forays the company will search not for platinum and other pricey metals–the typical quarry of space | CONTINUED ON PAGE 78

JPL/MSSS/NASA



WHAT COULD POSSIBLY GO WRONG?

No Buck Rogers, No Bucks

Business as usual could spell the end of public support for space exploration

All hopes for space will come to nothing if the future resembles the present, with tight budgets and constantly changing plans. "I've been in the space business for 35 years," says Paul Spudis, a scientist at the Lunar and Planetary Institute, in Houston. "I've never seen such a screwed-up mess as we now have."

NASA's current plans call for sending humans to Mars in the 2030s, but any such trip is at least 60 years away, argues Ralph McNutt, a physicist at Johns Hopkins University's Applied Physics Laboratory, in Laurel, Md. "The price tags have come out to be so big that they're just not palatable." But Mars is easy for politicians to support, he says: They can advocate for the long-term goal without diverting enough funds today to make it happen.

Dithering could slowly eat away at public support. "I think the worst case would be if we continue only with these occasional piecemeal, individual missions that are kind of designed to be self-sustaining, like Conestoga wagons full of all the supplies you'll ever need," says Mason Peck, a professor of mechanical and aerospace engineering at Cornell and former chief technologist at NASA. "I think that will limit the amount of science that can be done and the amount of human exploration that we can do," Peck adds. "If that persists, I think eventually people will lose patience, and there will be less and less public support for space exploration and science generally. Then we'll never be able to get off the planet in a permanent way."

But even if the government does push aggressively to build space infrastructure, the effort could still falter. A "killer app" that would vastly change the economic equation and make space development profitable still hasn't been found. Scott Pace, director of the Space Policy Institute at George Washington University, in Washington, D.C., phrases the problem like a riddle: "What's the question," he asks, "for which space is the answer?"

There are also practical hurdles, such as the legality of claiming asteroids and lunar resources, says Henry Hertzfeld, a professor of space policy and international affairs at George Washington University. "Who has the rights? Do we have to divide them up, and if so, how? These issues would have to be addressed," Hertzfeld says.

And if we somehow succeed in all our efforts, there could be side effects. For instance, we might spoil pristine environments of historical or scientific significance. Picking the path forward for space won't be easy, but if we don't carefully consider it, the choice could be made for us. *—R.C.*

IN THE RED: Is Mars too giant a leap?

ILLUSTRATION BY **MCKIBILLO**

INFINITELY MALLEABLE MATERIALS

People will conjure objects as easily as we now play music or movies

By **Philip Ball**

SEVERAL EXECUTIVES LISTEN ATTENTIVELY TO A SHARP-suited sales rep making his pitch. Suddenly, a miniature car emerges from a vat of gray goop in the center of the conference table. The salesman proceeds to reshape this model using nothing more than his hands, flattening the car's roofline and adjusting the geometry of its headlamps. Finally, he transforms the car from its initial haze gray to fire-engine red, its "atoms" twinkling in close-up with Disney-movie magic as their color changes. • Yes, it's just a video done with special effects. But it comes from researchers at Carnegie Mellon University, in Pittsburgh, who are developing technology intended to enable not just the instant creation of complex objects–far beyond what today's 3-D printing can achieve–but also their transfiguration on command. • Such a capability could change society even more profoundly

PHOTOGRAPH BY Adam Voorhes

than the Internet has. If this magical morphable matter were cheap and effective, it would allow us to send and download copies of objects as easily as we do digital documents. We could duplicate an object and then reshape it to our whims. Even if the technology turns out to be too expensive or the objects too fragile to replace conventionally manufactured goods, it might still allow people to summon up a facsimile of the thing they desire long enough to test it out, try it on, redesign it, or be entertained by it—with no more effort than it now takes to view a digital movie or play an MP3 file.

But do such wild notions bear any relation to what might actually be possible over, say, the next 50 years? To get a sense of the answer, it's helpful first to look back a quarter century or so to the roots of this audacious concept.

IN 1991, MIT COMPUTER SCIENTISTS Tommaso Toffoli and Norman Margolus speculated in print about a collection of small computers arranged so that they could communicate with their immediate neighbors while carrying out computations in parallel. A large number of such computing nodes would together constitute "programmable matter," according to Toffoli and Margolus. They were talking only about a highly parallel modular computer, one that might simulate the physics of real matter. But soon others applied this same term to a far more ambitious idea: an assembly of tiny robotic computers that could rearrange themselves to take on varying forms.

The chemistry Nobel laureate Jean-Marie Lehn independently developed related ideas even earlier, but coming from a different direction. He and others argued that chemists would use the principles of self-organization to design molecules imbued with the information they needed to spontaneously assemble themselves into complex structures. In the 1980s, Lehn began calling this "informed matter," which would be a kind of programmable matter constructed at the atomic and molecular scale.

The last decade or so of research in nanotechnology—with its interest in "bottom-up" self-organizing systems—has lent increasing support to Lehn's ideas. But creating molecules that can assemble into complex and even responsive forms is one thing; designing systems made from tiny computers that will reconfigure themselves into whatever you want at the push of a button is a whole other kind of challenge. For that, it's the engineers who are now taking the lead.

The shrinking of power sources and circuitry for wireless communications now allows robots, even centimeter-size ones, to talk to one another easily. And making miniature machines that can change shape or orientation without requiring delicate moving parts is increasingly practical, thanks to the development of smart materials that respond to external stimuli by bending or expanding, for example.

In short, in the three decades since the basic ideas of programmable matter were first formulated, the technologies needed to create concrete examples have arrived and are actively being tinkered with.

SETH GOLDSTEIN AND HIS TEAM AT Carnegie Mellon, in collaboration with others at Intel Research Pittsburgh, were among the first to put together prototypes and explore possible applications.

Goldstein and his colleagues envision millions of cooperating robot modules, each perhaps no bigger than a dust grain, together mimicking the look and feel of just about anything. They hope that one day these smart particles—dubbed claytronics—will be able to produce a synthetic reality that you'll be able to touch and experience without donning fancy goggles or gloves. From a lump of claytronic goop, you'll be able to summon any prop you want: a coffee cup, a scalpel, or (as their promotional video illustrates) a model automobile to use in a sales presentation.

"Any form of programmable matter that can pass the Turing test for appearance [looking indistinguishable from the real thing] will enable an entire new way of thinking about the world," says Goldstein. He also entertains the notion that objects built from programmable matter could be fully functional, in which case the possibilities for this technology become so limitless as to boggle the mind. "Applications like injectable surgical instruments, morphable cellphones, and 3-D interactive life-size TV are just the tip of the iceberg," says Goldstein.

The Carnegie Mellon team calls the components of this stuff "catoms," short for claytronic atoms, tiny spherical robots that are able to move, stick together, communicate, and compute their location in relation to others. Making them is a tall order, especially if you need millions. But Goldstein thinks it's achievable.

TIME CAPSULE: 1964

IBM SYSTEM/360

When it was introduced in April 1964, IBM's System/360 was the first commercially available mainframe based on integrated circuits. The machine ranged in speed from 0.0018 to 1.7 million instructions per second. By comparison, the iPhone 5s can execute around 18 200 MIPS.

PHOTO-ILLUSTRATION BY Gluekit

Since the early 2000s, he and his fellow Pittsburgh researchers have been building modest approximations of their ultimate goal. The first prototypes were squat cylinders, each a little bigger than a D-cell battery, their edges lined with rows of electromagnets, which allowed them to stick to one another and form two-dimensional patterns. By turning various magnets on and off in sequence, the researchers could make one catom crawl around another. More recently, the team used photolithography to build cylindrical catoms about a millimeter in diameter, which can receive power, communicate, and adhere. These tiny catoms can't yet move, but they will soon, Goldstein promises.

The key challenge is not in manufacturing the circuits but in programming the massively distributed system that will result from putting all the units together, says Goldstein. Rather than drawing up a global blueprint, the researchers hope to use a set of local rules, whereby each catom needs to know only the positions of its immediate neighbors. Properly programmed, the ensemble will then find the right configuration through an emergent process.

Some living organisms seem to work this way. The single-celled slime mold *Dictyostelium discoideum*, for example, aggregates into a multicellular body when under duress, without any central brain to plan its dramatic transformation or subsequent coordinated movements.

For catoms to do that, they must first be able to communicate with one another, if not also with a distant controller. The Carnegie Mellon researchers are now exploring electrostatic nearest-neighbor sensing and radio technologies for remote control.

Of course, to be practical, the repositioning of catoms needs to happen fast. Goldstein and his colleagues think that an efficient way to produce shape changes might be to fill the initial blob

PREVIOUS PAGE: PROP STYLIST: ROBIN FINLAY

ILLUSTRATION BY **MCKIBILLO**

WHAT COULD POSSIBLY GO WRONG?

Help, My Chair Has a Virus!

Hackers could turn your programmable matter against you

There is something a little sinister in this idea of matter that morphs and even mutates. Can we be sure we can control this stuff? Here our fears are surely shaped by old myths like the golem of Jewish folklore, a being fashioned from clay that threatened to overwhelm its creator.

The malevolence of matter that is infinitely protean is also evident in popular culture, for example the "liquid robot" T-1000 of *Terminator 2: Judgment Day* (1991). The prospect of creating programmable matter this sophisticated remains so remote, though, that such dangers can't be meaningfully assessed. But in any event, Seth Goldstein of Carnegie Mellon insists that "there's no gray-goo scenario here," referring to a term that nanotechnology visionary K. Eric Drexler coined in his 1986 book *Engines of Creation*.

Drexler speculated about the possibility of nanobots that could self-replicate exponentially as they consumed the raw materials around them. This sparked some early fears that out-of-control nanotechnology could turn the world into a giant mass of gray sludge—a theme that appeared repeatedly in later works of science fiction, including Wil McCarthy's 1998 novel *Bloom*, the late Michael Crichton's 2002 thriller *Prey*, and even in tongue-in-cheek fashion in a 2011 episode of the animated TV sitcom "Futurama."

The real threats may be ones associated more generically with pervasive computing, especially when it works by means of Wi-Fi. What if such a system were hacked? It's one thing to have data manipulated online this way, but when the computing substrate is tangible stuff that reconfigures itself, hackers will gain enormous leverage for creating havoc.

But Goldstein thinks that the actual dangers are more of a sociological nature. Programmable matter is sure to be rather expensive, at least initially, and so the capabilities it offers might only widen the gap between those with access to new technology and those without. Want to relax on your home holodeck? Enjoy it if you can afford one. If not, you'll have to content yourself with playing *Grand Theft Auto XXXVII*.

And if programmable matter becomes capable of producing fully functional objects, that development, much like today's pervasive automation, will threaten to render jobs in traditional manufacturing obsolete. So serious advances in programmable matter will probably make more people unemployable, not because they lack useful skills but because there will be nothing for them to do.

Of course, powerful new capabilities always carry the potential for abuse. You can see hints of that already in, say, plans to use swarm robotics for surveillance or in the reconfigurable robots that are being designed for warfare. Expect the dangers of programmable matter to be much like those of the Internet: When just about everything is possible, not all of what goes on will be good. *—P.B.*

of catoms with lots of little voids and then shift *them* around to achieve the right contours. Small local movements of adjacent catoms would be sufficient to shift the cavities, and if they are allowed to bubble to the surface, the overall volume would shrink. Conversely, the material could expand by opening up pockets at the surface and engulfing them.

AT MIT, THE COMPUTER SCIENTIST Daniela Rus and her collaborators have a different view of how smart, sticky grains could reproduce an object. Their "smart sand" would be a heap of such grains that stick together selectively to form the target object. The unused grains would just fall away.

Like Goldstein, Rus and her colleagues have so far built only rather large prototypes—"smart pebbles"—that work in two dimensions, not three. These units are the size of sugar cubes, with built-in microprocessors and electromagnets on four faces. A set of cubes can duplicate a shape inserted into the midst of a group of them. The ones that border the target object recognize that they are next to it and send signals to a collection of other cubes elsewhere to replicate its shape.

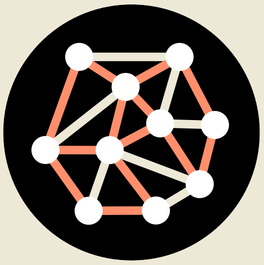
Rus's team hit on an ingenious way to make smart grains move, demonstrating the strategy using larger cubes they call M-blocks, which are 5 centimeters on a side. Each uses the momentum of flywheels spinning at up to 20 000 rotations per minute to roll over, climb on top of one another, and even leap through the air. When they come into contact, the blocks can be magnetically attached to form the desired configuration. At the moment, the experimenters must provide the instructions for sticking together. Their plan, though, is to develop algorithms that allow the cubes themselves to decide when they need to hook up.

The researchers' ultimate aim is to create a system of modules the size of sand grains that can form arbitrary structures with a variety of material properties, all on demand. Shrinking today's robotic pebbles and blocks to the submillimeter scale presents an enormous technical challenge, but it's not unreasonable to imagine that advances in microelectromechanical systems might allow for such miniaturization a few decades from now. That would then allow someone to instantly reproduce a facsimile of just about any object—depending on what it is, maybe even one that functions as well as the original.

While the holy grail is a sea of tiny machines working together to perform such magic, Goldstein sees the basic ideas of programmable matter being applied to objects at all scales, from atoms to house bricks, or perhaps even larger. It's almost a philosophy: a determination among today's researchers to make their creations more intelligent, more obedient, and more sensitive, imbuing them with qualities that will eventually make them act almost like living things—like matter with a mind of its own. ■

Programming Matter From the Bottom Up

Chemists, too, hope to fashion programmable forms of matter



Engineers' top-down approaches to programmable matter will build on existing developments in robotic technology. But there are also bottom-up strategies, using nanoscale particles or even molecules. For example, there is intense research being done on self-propelled or "living" colloids: particles perhaps a hundred or so nanometers across that have their own means of propulsion, such as chemical reactions that release gas.

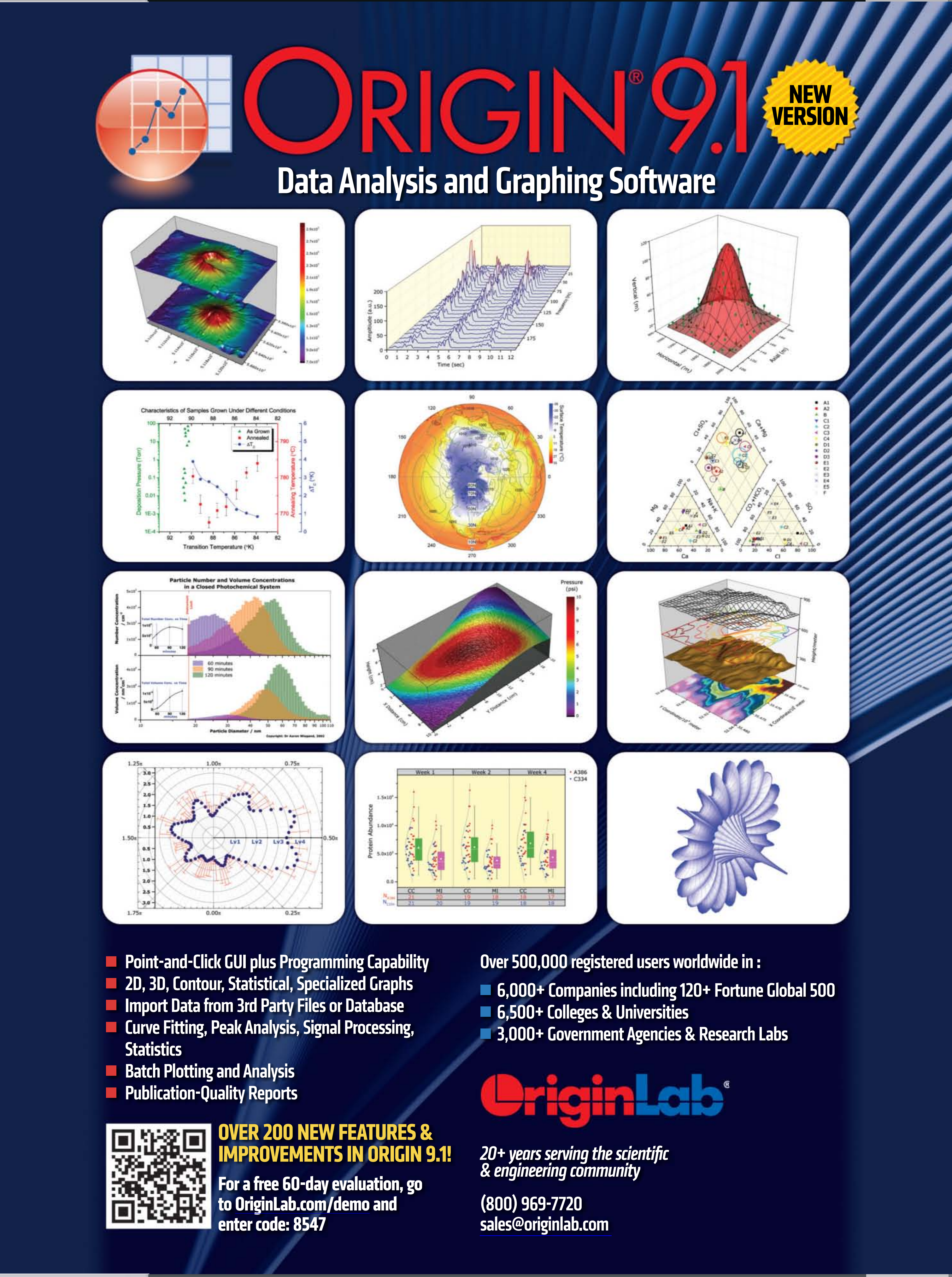
These particles, made from materials like magnetic crystals encapsulated in polymer spheres, can exhibit complex, self-organized behavior. They can, for instance, form crystalline patterns that break or even explode and then re-form. Choreographing these changes is impossible at the moment, but researchers have shown they can move and control individual nanoparticles using radio waves and magnetic fields. These same techniques have also permitted wireless remote control of certain processes in living organisms, such as the triggering of nerve signals and the release of insulin. So it's not too huge a leap to envision their use in some future form of configurable matter that might be used to modify, heal, or control living things.

Researchers have also been studying ways to turn DNA itself into a kind of programmable material that could be made to assemble into specific configurations using the same chemical principles that bind the double helix of the genome. In this way, scientists have woven strands of DNA into complex nanoscale shapes: boxes with switchable lids, letters of the alphabet, even tiny world maps. By supplying and removing "fuel strands," which can temporarily stick to and change the shape of other strands, it's even possible to make molecular-scale machines that move.

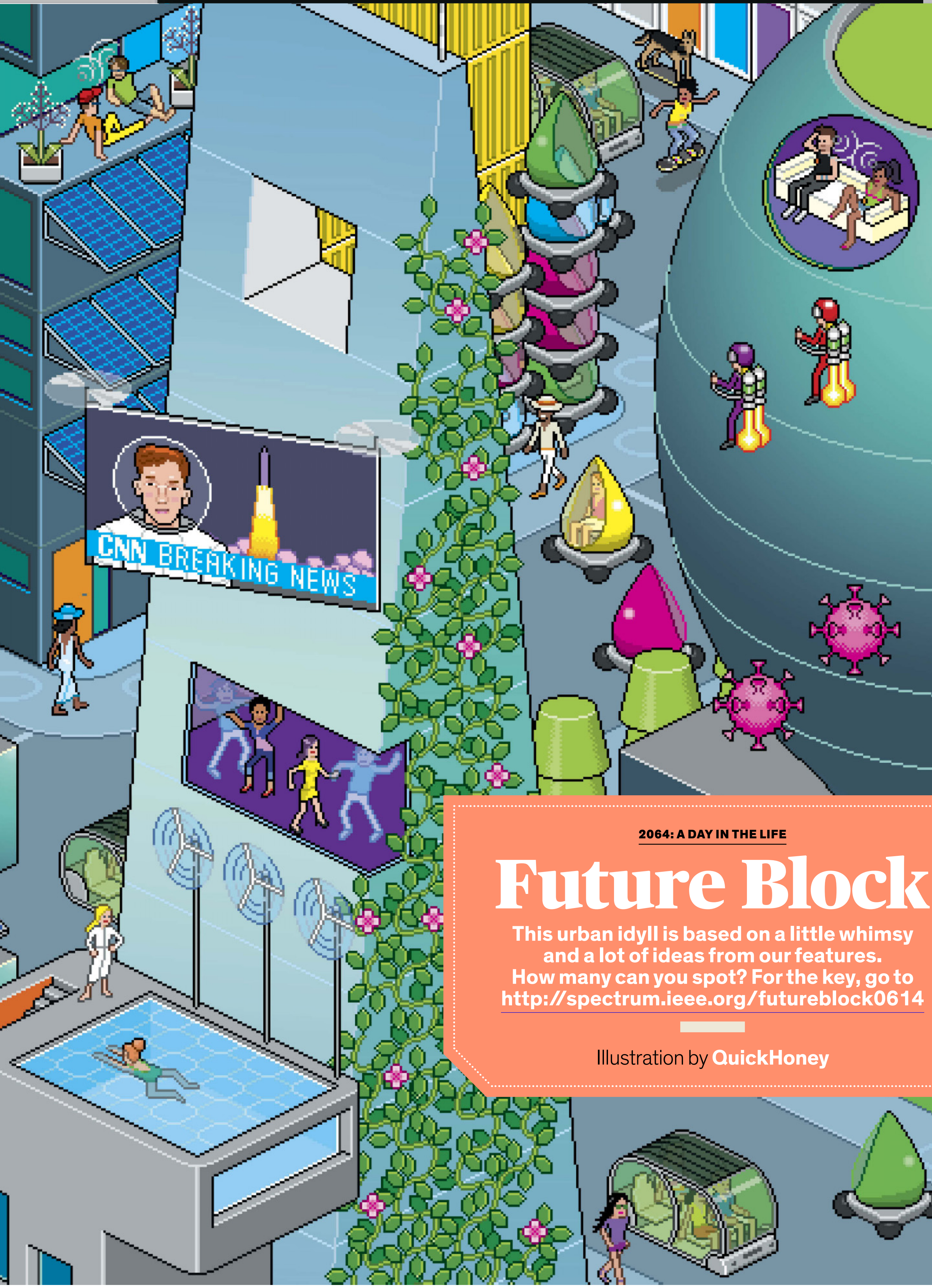
Eventually, such DNA bots might be given the ability to replicate and evolve, at which point this variety of programmable matter could become increasingly complex and capable on its own. —*P.B.*

POST YOUR COMMENTS at http://spectrum.ieee.org/science0614

ILLUSTRATION BY Greg Mably


ORIGIN® 9.1
NEW VERSION
Data Analysis and Graphing Software
Point-and-Click GUI plus Programming Capability
2D, 3D, Contour, Statistical, Specialized Graphs
Import Data from 3rd Party Files or Database
Curve Fitting, Peak Analysis, Signal Processing, Statistics
Batch Plotting and Analysis
Publication-Quality Reports
OVER 200 NEW FEATURES & IMPROVEMENTS IN ORIGIN 9.1!
For a free 60-day evaluation, go to OriginLab.com/demo and enter code: 8547
Over 500,000 registered users worldwide in :
6,000+ Companies including 120+ Fortune Global 500
6,500+ Colleges & Universities
3,000+ Government Agencies & Research Labs
OriginLab®
20+ years serving the scientific & engineering community
(800) 969-7720
sales@originlab.com

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page



2064: A DAY IN THE LIFE

Future Block

This urban idyll is based on a little whimsy and a lot of ideas from our features. How many can you spot? For the key, go to http://spectrum.ieee.org/futureblock0614

Illustration by **QuickHoney**

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

MOVIES

THE FUTURE WE DESERVE

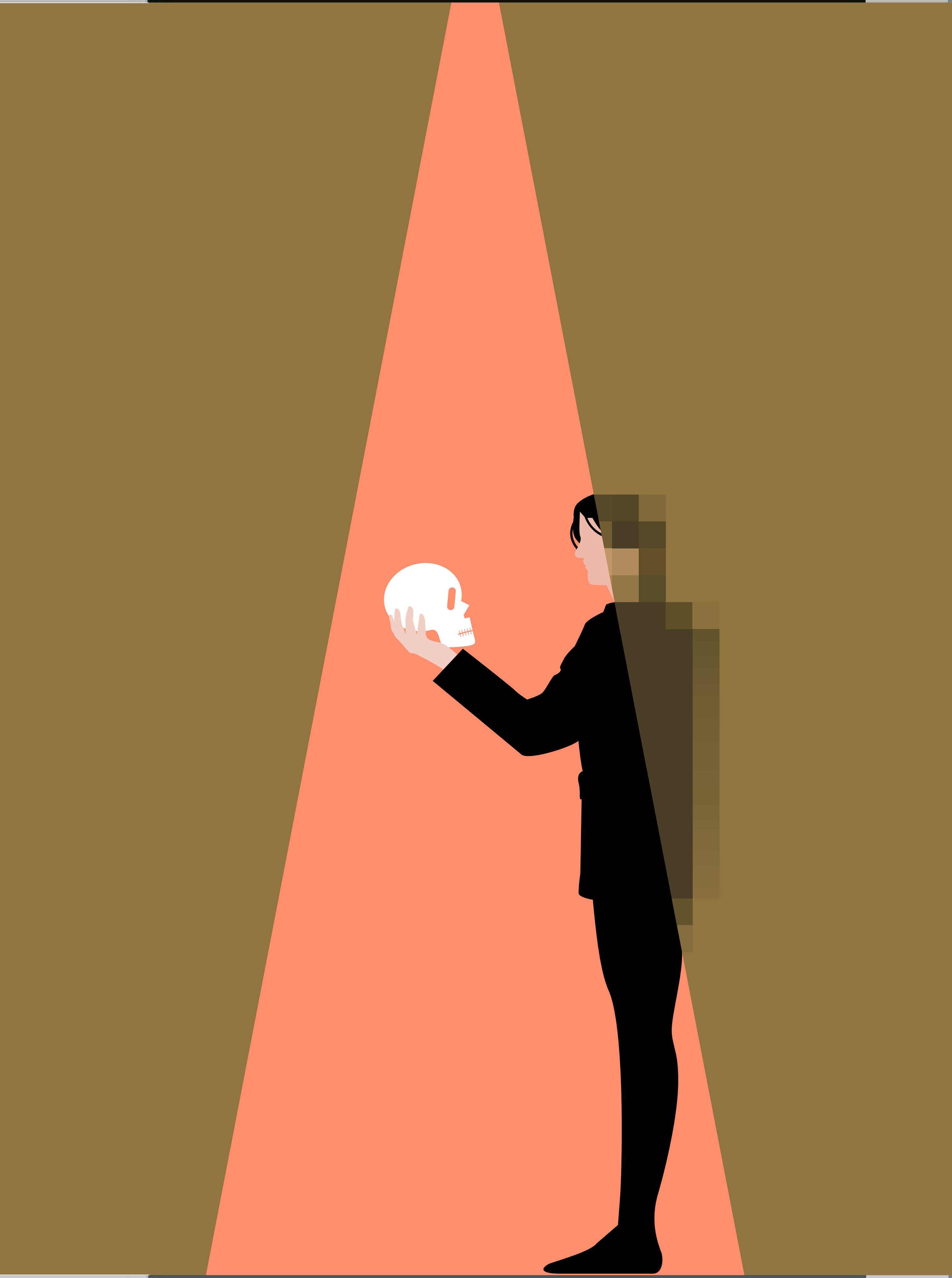
LEAVING THE UNCANNY VALLEY BEHIND

Computer-generated humans are paving the way for new forms of entertainment

By Tekla S. Perry

SAY HELLO TO IRA. HIS HEAD IS VISIBLE ON A SCREEN, AS though he's in a videoconference. He seems to be in his early 30s, with a shaved head, a pronounced nose, and thin eyebrows. Ira seems a little goofy and maybe just a wee bit strange. But unless you knew his full name—it's "Digital Ira"—you probably wouldn't guess that he's nothing but bits. • In the background, a graphics processor churns through the calculations that determine every roll of his eyes, every crease or bulge of his skin, and every little arch of his eyebrow. Digital Ira can assume almost any expression—joy, befuddlement, annoyance, surprise, concern, boredom, or pleasure—in about the same amount of time it takes a human to do so. • As Digital Ira affirms, graphics specialists are closing in on one of their field's longest-standing and most sought-after prizes: an interactive and

ILLUSTRATION BY Ben Wiseman



ACROSS THE VALLEY: A digital re-creation of the late rapper Tupac Shakur performed at the 2012 Coachella festival [top], Brad Pitt's digital double aged dramatically in the 2008 movie *The Curious Case of Benjamin Button* [bottom left], and researchers at the University of Southern California's Institute for Creative Technologies have created a strikingly realistic virtual human, Digital Ira [bottom right].

photo-realistically lifelike digital human. Such a digital double will change the way we think about actors, acting, entertainment, and computer games. In movies, digital doubles already replace human actors on occasion, sometimes just for moments, sometimes for most of a feature film. Within a decade or so, computer-game characters will be as indistinguishable from filmed humans as their movie counterparts. And in time, this capability will help bring movies and games together, and out of the union will come entirely new forms of entertainment.

This blurring of the real and the digital became possible in movies recently when moviemakers reached a long-anticipated milestone: They crossed the "uncanny valley." The term has been used for years to describe a problem faced by those using computer graphics to depict realistic human characters. When these creations stopped looking cartoonish and started approaching photo-realism, the characters somehow began to seem creepy rather than endearing. Some people speculated that the problem could never be solved; now it has proved to be just a matter of research and computing power.

Producing a fully realistic digital double is still fantastically expensive and time-consuming. It's cheaper to hire even George Clooney than it is to use computers to generate his state-of-the-art digital double. However, the expense of creating a digital double is dependent on the costs of compute power and memory, and these costs will inevitably fall. Then, by all accounts, digital entertainment will enter a period of fast and turbulent change. An actor's performance will be separable from his appearance; that is, an actor will be able to play any character—short, tall, old, or young. Some observers also foresee a new category of entertainment, somewhere between movies and games, in which a work has many plotted story lines and the viewer has some freedom to move around within the world of the story.

Creators of entertainment also dream that technology will someday make itself invisible. Instead of painstakingly using cameras and computers to share their visions, they hope to be able to directly share the rich worlds of their imaginations using a form of electronic mind reading far more sophisticated than the brain-scan technology of today: If you can think it, you will be able to make someone see it.

"That is the future I wish for—where the hard edges of technology disappear and we return to *magic,*" says Alexander McDowell, a professor at the University of Southern California's School of Cinematic Arts.

That magic means not only being able to step inside a realistic virtual world without the cumbersome—and, for some, nauseating—head-mounted screens that create virtual experiences today. It means being able to seamlessly merge the real and the virtual, to allow computer-generated beings to walk among real humans.

"I want to be able to jump down the rabbit hole—not just metaphorically, not just visually, but really jump inside" a story or virtual experience, says Tawny Schlieski, a research scientist at Intel Labs. "And I want the rabbit to follow me home."

Today's world of moviemaking—in which realistic computer-generated humans are an option, albeit an expensive one—was hard to imagine just 10 years ago. In 2004, the state-of-the-art computer-generated human was a creepily cartoonish Tom Hanks in *The Polar Express*. And the uncanny valley seemed an impossibly wide chasm.

CLOCKWISE FROM TOP: CHRISTOPHER POLK/GETTY IMAGES; ACTIVISION R&D/USC ICT; ALAMY

But just four years later, *The Curious Case of Benjamin Button* spanned the gap, in the opinion of most movie effects specialists. This motion picture, shifting seamlessly between Brad Pitt and a computer-generated replica of him, revolves around a boy who is born old and ages backward. It was "the Turing test" for computer graphics, says Alvy Ray Smith, who pioneered the use of computer graphics in movies at Lucasfilm in the 1980s and cofounded computer-graphics trailblazer Pixar. "I'd swear it was Brad Pitt right there on the screen–and I'm an evil-eyed, annoying computer-graphics expert," Smith says. The Turing test, named for the computer pioneer Alan Turing, gauges whether a machine is indistinguishable from a human and was originally proposed in 1950 to test natural-language conversations.

It's cheaper to hire George Clooney than it is to generate his digital double

Since *Benjamin Button*, pioneering moviemakers have begun to buttress the bridge across the uncanny valley, often for short scenes where it is impossible or inconvenient to film an actor directly. For example, a digital double replaced actor Guy Pearce in a few scenes in *Iron Man 3* because they were filmed after Pearce had grown a beard for his next project, reports Joe Letteri, senior visual-effects supervisor at New Zealand-based Weta Digital. And a digital version of the late rapper Tupac Shakur performed at the Coachella music festival in 2012.

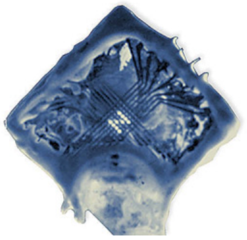
Creating these scenes took a lot of time and computing power. Each *frame* of a movie that uses computer-generated humans may take as many as 30 hours to process, using many racks of extremely high-powered computer servers. And just 5 minutes of film requires 7200 frames, at the now standard rate of 24 frames per second. Those figures mean that realistic digital doubles are beyond the reach of video-game creators–at least for now.

"The technology that we've developed does push down to games, but it's driven on the film side," says Letteri. Weta, which produced the effects for such blockbusters as *Avatar*, *The Lord of the Rings*, and the 2005 *King Kong*, is the world's leading practitioner of the effects technique known as motion capture. "Games have to put an image on the screen every 60th of a second; for us in movies, we will spend tens of hours getting a frame right."

Game makers believe that digital doubles, indistinguishable from human actors, will start appearing in games within a decade. It's Digital Ira that has made them so optimistic. Digital Ira starts with image data created by a sophisticated 3-D scanning system at USC's Institute for Creative Technologies, in Los Angeles. Graphics processors turn the data into a moving image by using calculations that determine not only the movement of the bones, muscles, and skin but also how light in the scene needs to reflect and scatter to best mimic how real light illuminates a real face as it talks, smiles, or frowns. Each individual frame appears on screen as it becomes available, at a rate of 60 frames per second. So far, two versions of a moving, speaking Digital Ira have been demonstrated: by Nvidia at the March 2013 GPU Technology Conference and by Activision at the July 2013 Siggraph conference. The Nvidia version ran on a Nvidia graphics card performing 4.9 trillion mathematical operations per second; the Activision version ran on a PlayStation 4 with a 1.84-teraflop graphics processor.

For game makers, being able to demonstrate a photo-realistic human created by computer graphics software on the fly was like throwing a rope across the uncanny valley–it made it possible for them to imagine that they, too, will be able to bridge that expanse soon. Says Jen-Hsun Huang, CEO of Nvidia, "In technology, if something is possible now, it will take less than 10 years to make it practical." He figures that a Digital Ira-level character will be available to computer-game producers within 5 years and that "we'll see video games with as much realism as *Gravity* in less than 10 years." At first, he adds, the technology will be used in limited ways, in games with relatively small numbers of characters or less complex worlds. And questions remain. It's one thing to present a digital human on the screen and expect you to see it as real; it's quite another to maintain the illusion of reality when you're interacting with the character, not just observing it.

THE FIRST MAJOR CHANGE WE'LL SEE in the entertainment world, probably about 10 years from now, when moviemakers and game creators are cranking out digital humans with ease, will be the separation of the actor's appearance from the actor's performance. In *Benjamin Button*, Brad Pitt's character changed dramatically but was always recognizable as Brad Pitt. Soon though, says graphics pioneer Smith, "it won't matter what the actor looks like anymore. He can be any age, any color. He can be a seven-foot basketball player with polka dots." But far from being the end of human actors, such advances may help actors blossom in ways not possible today. Imagine how many more roles Meryl Streep and Judi Dench could play if they weren't limited by their ages and physical conditions.



TIME CAPSULE: 1964

PLASMA DISPLAY PANEL

The first plasma display panel, demonstrated in 1964, was a scant 4 by 4 inches. Its inventors, Donald L. Bitzer, Hiram Gene Slottow, and Robert Wilson, at the University of Illinois at Urbana-Champaign, were recognized with an Emmy Award in 2002 for their achievement.

Next, when game characters are indistinguishable from movie actors, we're likely to see the emergence of a type of entertainment that lies somewhere between movies and games–Intel's Schlieski uses the informal term "cinemagraphic games." It will be years, maybe a decade or more, before the technical and creative factors align to produce a breakthrough work in the fledgling genre. But in the meantime, there have been a few glimmers of what's coming.

The game *The Walking Dead* is probably the best example, says Schlieski. In it, players have to do more than shoot; they have to make choices, such as whether to lie to characters, including a little girl and a police officer. The choices come back to help–or haunt–them later in the game. For example, after you've picked up the little girl you meet some strangers, and you need to lie to the strangers about your relationship to the girl. At that point, if the girl trusts you, she will support your lie and help you; if she doesn't, she won't.

Most efforts to blend movies and games have focused on the creation of a world for the player to explore. But just sending people into a virtual place to play isn't real entertainment.

"Stories have to be authored," says USC's McDowell. "But multiple threads can exist, and the audience can walk around in a story's landscape, following a major character and then diverting when another character seems more interesting." Theater artists have already started to embrace this model. *Sleep No More* is an interactive version of *Macbeth* that has been playing since 2011 in New York City. In the production, actors perform throughout a five-story building. Audience members move freely, following sets of actors or exploring the many rooms as they wish. The digital equivalent of this will come, although the details of how it will become a compelling experience are elusive. Schlieski believes the solution will hinge on plots. "What drives this industry is storytellers," she says. "Storytelling is an art and a gift."

THE ENTERTAINMENT INDUSTRY will spend decades exploiting the possibilities of digital characters. And much of that will be mere preamble to real revolution, four or five decades from now: teaching computers to act.

Today's computer-generated characters get their "acting" from real actors, using motion-capture technology: Live actors perform on a special stage, wearing tight jumpsuits studded with dozens of reflectors placed at key points on their bodies; they may also have reflectors or fluorescent paint on their faces. In some cases, head-mounted cameras capture their facial motions from multiple angles.

Motion-capture technology will get easier and more natural to use. But, says Javier von der Pahlen, director of creative research and development at the Central Studios division of Activision, "I would like to see a character that is expressing itself, not precaptured, not generating canned expressions or creating them from semantic rules, but creating expressions by the same things that create our expressions."

Weta's Letteri describes this approach as turning the process of generating characters around and driving it "from the inside out–to be able to ask, What is this character thinking, and how does that relate to his face?"

To do this will require overcoming many huge challenges. A truly digital character, one that does its own acting rather than conveying the acting of another actor, will be created only by merging artificial-intelligence technology that passes the Turing test in both verbal and nonverbal responses–physical gestures, facial expressions, and so on–with perfectly rendered computer graphics. That will be really hard.

Computer scientists don't think the challenge is insurmountable, but they agree that the complexity of the challenge is awe inducing, because even the nature of the goal is hard to spell out. "We don't have a clue how to replace actors," Smith says. "We don't know what acting is. None of us can explain how an actor convinces you that he or she is someone other than who they are."

Not only do scientists not know how actors generate emotions from a script, they don't even know how genuine emotions work to change the appearance of the face and body.

"Researchers have yet to agree whether we pull our facial expression first–a smile, say–and then feel happy, or if we feel happy and then smile to com-

PHOTO-ILLUSTRATION BY Gluekit

[redacted]

municate it," says Angela Tinwell, senior lecturer in games and creative technologies at the University of Bolton, in the United Kingdom.

Sebastian Sylwan, Weta's chief technology officer, is optimistic nevertheless. "Computer graphics is at most 30 years old," he notes. "And digital doubles have just arrived."

A half century from now, when we've become accustomed to seeing utterly convincing digital doubles, what will we wish we had done today? Collected the raw data to perfectly re-create historical figures, says Nvidia's Huang. Right now, we should be using digital motion-capture techniques to record world figures giving speeches, being interviewed, or performing, just as painters captured influential figures beginning in the 17th century and photographers in the 19th. "We should capture Obama, the Dalai Lama, all the people of consequence in the world," Huang says. "Once we capture it, we can enjoy it in ever-increasing fidelity as computer graphics advances."

Farther out, probably more than 30 years from now, digital humans–maybe displayed as holograms, maybe as robots–will be able to interact convincingly and satisfyingly with us. Ultra-advanced processors and software will let them interpret our thoughts and feelings and respond inventively with humor and compassion. "This could help reduce loneliness in an increasingly aging population," says Tinwell.

It's possible that these digital entities will employ a form of astoundingly sophisticated mimicry, mastering the memories, the social conventions, and the messy welter of emotions that underpin human relationships. They'll either understand us or fake it so well it won't matter.

And to quote the movie title, *that's* entertainment. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/movies0614

ILLUSTRATION BY **MCKIBILLO**

WHAT COULD POSSIBLY GO WRONG?

When the Fake Trumps the Real

In a world of synthetic faces, human expression could become hard to read

Computer-generated characters that are indistinguishable from humans are today typically limited to cameo appearances in action movies, except in a few rare and costly feature films. But when they become the norm on video-game displays as well as on cinema screens, they might not only play interactive games with us. They might start playing lasting games with our minds.

The human brain evolved to understand the subtle cues of people's emotions in order to anticipate their future behavior. When we lived in caves, that understanding could mean the difference between life and death. While computer-generated characters may, on the surface, be indistinguishable from their human counterparts, no one believes they'll be reflecting all the nuances of human expression anytime soon. Even so, people will likely spend more and more time interacting with them. They'll not only be entertainers but also teachers and customer-service agents. And there lies the danger, according to Angela Tinwell, senior lecturer in games and creative technologies at the University of Bolton, in the United Kingdom. When children grow up spending much of their days interacting with realistic computer-generated characters, says Tinwell, they may be handicapped when it comes to interacting with the real thing.

On the other hand, it's equally possible that the brain will adapt and learn new ways to distinguish the genuine human from the virtual impostor, says Ayse P. Saygin, associate professor of cognitive science and neurosciences at the University of California, San Diego.

But even in that best-case scenario lurks a major potential problem. A person who spends much of his childhood in virtual worlds might not want to leave them, Saygin says. When a game can adapt to your mood better than most acquaintances do, people might prefer the game to the friends. "When you go into the real world and people, unlike a game, are not engineered to entertain you and cater to your needs, or don't understand automatically when you are annoyed or happy, you will want to go home and hang out with your avatar friends," says Saygin. "I absolutely believe this technology will do a lot of good. But replacing human relationships could be the dark side of this."

Writers and directors have already started to explore such themes. The 2013 film *Her* spins a tale around a man who develops a romantic relationship with what the movie calls an intelligent "operating system," akin to an extremely smart Siri.

"Sometimes," Saygin says, "I think, in the Darwinian way, that things that aren't good for us won't be part of our future. But look at smoking—people got addicted even though it was bad for them, and we are only now correcting that behavior." *—T.S.P.*

ENERGY

THE FUTURE WE DESERVE

THE RISE OF THE PERSONAL POWER PLANT

Agile power systems will let every home and business generate, store, and share electricity

By Jean Kumagai

AT FIRST GLANCE, DOWNTOWN FORT COLLINS, COLORADO, looks like a sweet anachronism. Beautifully preserved 19th-century buildings beckon from leafy streets. A restored trolley car ding-dings its way along Mountain Avenue. It's safe and spotless, vibrant and unrushed. • And yet this quaint district is ground zero for one of the most ambitious energy agendas of any municipality in the United States. Fort Collins, population 150 000, is trying to do something that no other community of its size has ever done: transform its downtown into a net-zero-energy district, meaning it will consume no more energy in a given year than it generates. And the city as a whole is aiming to reduce its carbon emissions by 80 percent by 2030, on the way to being carbon neutral by midcentury. To make all that happen, engineers there are preparing to

PHOTOGRAPH BY Adam Voorhes

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

aggressively deploy an array of advanced energy technologies, including combined-cycle gas turbines to replace aging coal-fired plants, as well as rooftop solar photovoltaics, community-supported solar gardens, wind turbines, thermal and electricity storage, microgrids, and energy-efficiency schemes.

It's an audacious plan. But for Fort Collins Utilities, the local electric company, the less daring options were unacceptable. Like utilities all over the world, it is grappling with the dissolution of the traditional regulated-monopoly model of electricity production, with its single, centralized decision maker. The costs of solar and wind electricity generation have fallen to the point that countless consumers in many countries now produce their own electricity, often (but not always) with the blessing of regulators and policymakers.

The question now is, how far do we want to go? In the coming decades, technology will let us radically decentralize the grid, enabling businesses, factories, campuses, and households to provide their own electricity for much of the day and most of the year. Solar energy, fuel cells, and wind turbines will all be cheaper than they are now. Power requirements will also be reduced, because heating, cooling, appliances, and lighting will all be more efficient. Advances in batteries and other forms of energy storage will make it easier to ride out the inevitable variations in solar and wind power and the reactive-power challenges that will arise. And smart grids, microgrids, and other technologies will knit these many microgenerators together in nimble networks that will let people sell excess energy and capacity while drawing from the main grid as needed.

Taken together, these advances will underpin a more sustainable energy future, in which nuclear and fossil fuels play a gradually declining role and the effects of pollution, greenhouse gases, and nuclear waste are reduced. But large-scale changes to the power system can take decades to put into place. So now is the time to envision what the grid should look like in 2030 and beyond.

MORE BEER, FEWER WATTS: Solar panels at the New Belgium Brewing Co. in Fort Collins, Colo., supply 3 percent of the plant's electricity. The brewery is participating in the city's long-term plans to create a net-zero-energy downtown district and to become carbon neutral by midcentury.

PREVIOUS PAGE: PROP STYLIST: ROBIN FINLAY; THIS PAGE: NEW BELGIUM BREWING (3)

Such a future won't happen—in Fort Collins or anywhere else—without overcoming significant challenges. These include not just technological but also political and regulatory issues. Today, every time a homeowner installs photovoltaic panels on the roof and begins spinning the household electricity meter backward, every time a plug-in hybrid owner decides to charge up the car batteries, and every time a new wind turbine starts to turn, it perturbs the grid. Though those individual perturbations may be slight, as they begin numbering in the hundreds of thousands or even millions, the strain on a grid not designed to handle them will become potentially disastrous.

THE ELECTRICITY INDUSTRY IS UNdergoing the same sort of fundamental change that has already transformed telecommunications and computing, says Clark Gellings, a fellow at the Electric Power Research Institute (EPRI), in Palo Alto, Calif. Recall the heyday of the telephone landline, when a monopoly provided reliable service, with few bells and no whistles. Today, a multitude of telecom providers offer more wired and wireless options and services than most people, frankly, care to contemplate. Computers, similarly, used to mean giant mainframes accessed via remote terminals. But when CPUs and memory became cheap enough and powerful enough, people could own their own computers, access and exchange information via the Internet, and leverage the power of distributed computation in the cloud.

Gellings envisions an analogue for electricity that he calls the ElectriNet: a highly interconnected and interactive network of power systems that also combines telecommunications, the Internet, and e-commerce. (Gellings first unveiled the then-heretical notion of electricity customers managing their own usage–a concept he called "demand-side load management"–in the December 1981 issue of *IEEE Spectrum*.) Such a network will allow traditional utilities to intelligently connect with individual households, service providers, and as yet unforeseen electricity players, fostering the billions of daily electricity "transactions" that will take place between generators and consumers. Smart appliances in the home will be able to respond to changes in electricity prices automatically by, for instance, turning themselves off or on as prices rise or fall. The ElectriNet will also allow for home security, data and communication services, and the like.

In addition, Gellings says, advanced sensors deployed throughout the network will let grid operators visualize the power system in real time, a key capability for detecting faults, physical attacks, and cyberattacks and for preventing or at least mitigating outages.

While distributed generation is already taking hold in many places, Gellings notes, "we have to move toward a truly integrated power system. That's a system that makes the best use of distributed and central resources–because central power generation is not going to go away, although it may change in shape and form." [For more on the undesirability

WHAT COULD POSSIBLY GO WRONG?

The Slow Death of the Grid

Too many off-grid personal power stations will undermine communal infrastructure

The price of photovoltaic cells continues to plummet while their efficiency continues to rise. Batteries and other energy-storage technologies are also getting better, prompting more people to unplug from the grid. If current trends continue, the result could be catastrophic, not just for the utilities but for anyone who wants access to affordable, stable electricity.

Here's why. "When you have mass defection from the grid, that means many people are overinvesting in individual, unnetworked assets to meet their own peak energy demands," says James Mandel, a manager at the Rocky Mountain Institute, in Boulder, Colo. "As a result, it leaves those least able to afford a personal power station—low-income customers, those who rent or have bad credit—to pick up the cost of the grid." And those homeowners and businesses going it alone might find operating and maintaining their own "utility in a box" expensive and time-consuming, he adds. Needless to say, as their revenues erode, grid operators will hardly be viable. "That's a future we'd rather not see," Mandel says.

In some places, though, that future is already here. In Hawaii, where electricity rates are typically more than 40 cents a kilowatt-hour, having your own solar PV array with battery storage now makes economic sense for anyone who can afford it. In a recent report, *The Economics of Grid Defection*, the Rocky Mountain Institute predicted when that "grid parity" tipping point would occur in five U.S. regions. In Los Angeles and in New York's Westchester County, for example, it could happen as early as 2020. Advances in other local generation options, such as combined heat and power systems that run off hydrogen fuel cells, could encourage even more people to leave the grid.

The report was intended as a wake-up call, Mandel says. "When grid defection becomes viable, it's not a 'could happen,' it's a 'will happen.'" So six years or maybe a little longer, he says, "is how long we have to figure out a better model."

The preferred future, according to the report's authors and many other power experts, is a grid with even greater connectivity and smarts. The worst-case scenario, says Clark Gellings, a fellow at the Electric Power Research Institute, is that "the smart grid isn't really smart. It's dumb, and we don't get the interconnectivity right." In that bleak future, customers who once had access to relatively cheap and reliable service will face enormous price swings and frequent, chronic blackouts. And without a robust, sustainable grid, the other swell futures envisioned elsewhere in this issue—self-driving cars, household robots, thought-detecting wearable computers, and so on—won't come to pass either.

"My preferred vision of the future isn't at all inevitable," Gellings admits. "That's why I'm out there every day, traveling around the country, meeting with regulators and utilities, trying to get the message across." *—J.K.*

ILLUSTRATION BY MCKIBILLO

of grid defection, see the sidebar, "The Slow Death of the Grid."]

A highly intelligent and agile network that can handle the myriad transactions taking place among hundreds of thousands or even millions of individual energy producers and consumers isn't just desirable, say experts. It has to happen, because the alternative would be grim.

Just ask the Germans. Generous subsidies, called feed-in tariffs, for renewable energy resulted in the country adding 30 gigawatts of solar and 30 gigawatts of wind power in just a few years. On a bright breezy day at noon, renewables can account for more than half of Germany's generated electricity.

"That sounds like a good thing, but to the utility, it looked like a huge negative load," notes Benjamin Kroposki, director of energy systems integration at the National Renewable Energy Laboratory in Golden, Colo. When a large amount of renewable power is being generated, the output of conventional central power plants is correspondingly reduced to keep the system balanced. But if a local outage or a voltage spike or some other grid disturbance occurs, protective circuitry quickly shuts down the photovoltaics' inverters. (Inverters are semiconductor-based systems that convert the direct current from the solar cells to alternating current.) And that in turn can lead to cascading systemwide instabilities.

"If you lose 30 gigawatts in just 10 cycles"–two-tenths of a second, that is–"you can't ramp up conventional generators quickly enough to compensate," Kroposki notes. So the Germans had to spend the equivalent of hundreds of millions of dollars on smarter inverters and communication links that would allow the PV arrays to automatically ride through any disturbances rather than simply shut down.

Customers are paying dearly for those upgrades: Electricity rates in Germany have doubled since 2002, to about 40 U.S. cents per kilowatt-hour. That's more than four times the price of electricity in Illinois. Many other countries are now learning from these experiences, Kroposki adds, "to make sure that solar and wind systems integrate with the grid in ways that help overall system stability."

WATTS WHERE NONE EXISTED BEFORE: A reimagined energy future with more distributed generation, storage, and microgrids isn't just for people in wealthy countries. It will also include those who have no access to electricity—that's nearly 1.3 billion people right now. Indeed, it's already happening. SharedSolar, a project started by Columbia University's Vijay Modi and some of his students, is rolling out small photovoltaic arrays connected by a microgrid in villages across sub-Saharan Africa. Households and businesses prepay for their electricity, in much the same way they might prepay for cellphone service.

PHOTO: SHAREDSOLAR

A SIZABLE JAPANESE EXPERIMENT is taking such an integrated approach. At a site 30 minutes by train from central Tokyo, a real estate developer is turning an old golf course into a planned smart city called Kashiwanoha. Energy, water, and other public services for an eventual population of 26 000 are being intelligently managed at every scale, from individual households to businesses and factories to citywide networks.

The smart-city concept has been kicking around for a while. But it didn't really take hold in Japan until the Fukushima disaster in March 2011, says Akihiko Tobe, general manager of Hitachi's smart-city project division, which is furnishing the energy management systems for Kashiwanoha. "The earthquake changed everything," Tobe says. "Many cities suffered great damage, with power breakdowns and

TIME CAPSULE: 1964

CARBON DIOXIDE LASER

After finishing his Ph.D. at Stanford, C. Kumar N. Patel joined Bell Labs and led the team that in 1964 developed the most powerful continuously operating laser. The carbon dioxide laser is now used for cutting diamonds, analyzing the upper atmosphere, and removing tumors, among other things.

PHOTO-ILLUSTRATION BY Gluekit

water shutdowns. In tall buildings, elderly people were trapped on high floors because the elevators stopped working."

And so Kashiwanoha's electricity system is designed to provide uninterrupted service to critical systems like elevators, water pumps, and hospitals in the event of an emergency. To do that, it relies on several battery storage sites as well as a microgrid, which facilitates the sharing of electricity and can operate in isolation of the main grid. A command center on the second floor of a hotel and apartment building oversees the microgrid and tracks exactly where electricity is being consumed and generated. During normal operation, customers are also encouraged to track their own energy usage through touch-screen monitors in their homes and businesses. Those who do an especially good job of reducing their consumption are awarded "eco points," which they can exchange for goods and services at the local LaLaPort shopping center.

Eventually, says Tobe, more home automation will be added, like sensors that automatically turn off lights when the curtains are opened. Health-care monitoring will also be offered, to track things like how much exercise you get and how many calories you eat. People who move to Kashiwanoha realize that the city represents a break with the past, says Tobe. "Their mind-set is that they're establishing a new culture, and they're highly motivated to participate in making life better."

ASSUMING THAT FORWARD-LOOKING cities like Fort Collins and Kashiwanoha reach their energy goals, can that success be replicated? "A good electricity future will depend on every new technology you can think of," says EPRI's Gellings. "Energy storage, device efficiency, better ways to mine coal and extract natural gas, grid sensors, more advanced generation." Should any one of these technologies not progress in the way that experts now assume they will, it could throw a wrench in the works, he says. Regulators and policymakers will also need to be convinced to make the hefty investments in infrastructure that a smarter integrated grid will require.

> **"A good electricity future will depend on every new technology you can think of"**

Even if all these changes come to pass, the grid in 2064 will still look a lot like today's grid in some key ways. Big coal plants, for instance, will remain a large part of the energy mix. According to the U.S. Energy Information Administration's *International Energy Outlook 2013*, the United States, Australia, and many other countries will retire their aging coal plants, but other countries will continue to build new ones. China, already the world's leading coal user, will add about 530 gigawatts of coal-fired power capacity by 2040, the report projects. And so coal's share of electricity generation worldwide in 2040 will likely be just a few percentage points below what it was in 2010.

And once those new plants come on line, they'll be hard to budge. "This is a very inertial field," says Vaclav Smil, who's studied the slow pace of change in the power industry. "A single power plant costs like a billion dollars to build. Once you put it in place, you don't want to tear it out and start again. So innovation will happen mainly at the margins."

Innovation at the margins could still lead to profound changes in the future grid, if cities like Fort Collins and Kashiwanoha get it right. Fifty years from now, says Steve Catanach, manager of light and power at Fort Collins Utilities, the two coal-fired plants from which the city draws 80 percent of its electricity will no longer be active. Taking their place will be new combined-cycle gas turbines but also a larger share of distributed generation. These days, the utility is actively encouraging investments in wind and solar through a new feed-in tariff, which will let customers sell their electricity back to the grid at a guaranteed rate. Greater use of demand-response mechanisms will allow customers to curtail their usage during times of peak demand. And when energy storage becomes affordable, Catanach adds, "we'll use that to balance the variability of the renewables."

While some industry experts are wringing their hands over the looming "death spiral" for today's utilities, Catanach manages to sound optimistic about what's to come. "Fort Collins is a great place to live, and the lights are always on," he says. He's pretty sure that 50 years from now, people will still be able to say the same thing. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/energy0614

IEEE SPECTRUM | Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page | Qmags THE WORLD'S NEWSSTAND®

CARS

THE FUTURE WE DESERVE

ROBOT, YOU CAN DRIVE MY CAR

Autonomous driving will push humans into the passenger seat

By **Philip E. Ross**

SIXTY YEARS AGO THIS MONTH, ISAAC ASIMOV published a short story about a self-driving "automatobile" called Sally who had not only judgment but feelings, which spelled doom for the man who loved her. • It will happen–and it won't. Fully automated cars will be common. Those cars will have judgment, and this will upend our lives, our work, and our cities. But cars will have no more feeling than IBM's Deep Blue had back in 1997, when it beat the world chess champion. Well, two out of three isn't half bad, even for an Asimov. • Today you can buy a top-of-the-line S-Class car from Mercedes-Benz that figuratively says "ahem" when you begin to stray out of your lane or tailgate. If you do nothing, it'll turn the wheel slightly or lightly apply the brakes. And if you're still intent on crashing, it will take command. In 5 years, cars will be quicker to

ILLUSTRATION BY Ben Wiseman

THE FUTURE WE DESERVE

intervene; in 20, they won't need your advice; and in 30, they won't take it.

Accident rates will plummet, parking problems will vanish, streets will narrow, cities will bulk up, and commuting by automobile will become a mere extension of sleep, work, and recreation. With no steering column and no need for a crush zone in front of the passenger compartment (after all, there aren't going to be any crashes), car design will run wild: Collapsibility! Stackability! Even interchangeability, because when a car can come when called, pick up a second or third passenger for a fee, and park itself, even the need to own the thing will dwindle.

"When we modeled that for Ann Arbor, Mich., we found we'd need only 15 percent of the cars now owned there," for a per-mile cost savings of 75 percent, says Larry Burns, director of the Program on Sustainable Mobility at the Earth Institute of Columbia University, in New York City. Burns is no ivory-tower academic: In his previous job he headed up research and development for General Motors.

What's most striking about the new thinking is how suddenly it jelled. Two MIT economists, Erik Brynjolfsson and Andrew McAfee, write about the switch in their recent book, *The Second Machine Age,* in which they describe their 2012 spin in the Google self-driving car as almost "boring" because the car drove "exactly the way we're all taught to in driver's ed." They then note that the experience "was especially weird for us because only a few years earlier we were sure that computers would not be able to drive cars."

Many others were just as sure. Read what Frank Levy of MIT and Richard Murnane of Harvard wrote about the challenge of city driving back in 2004, in their book *The New Division of Labor:*

> As the driver makes his left turn against traffic, he confronts a wall of images and sounds generated by oncoming cars, traffic lights, storefronts, billboards, trees, and a traffic policeman. Using his knowledge, he must estimate the size and position of each of these objects and the likelihood that they pose a hazard.... Articulating this knowledge and embedding it in software for all but highly structured situations are at present enormously difficult tasks.

A YEAR AFTER THOSE LINES WERE written, Sebastian Thrun led the Stanford team's car to victory in the DARPA Grand Challenge, the Defense Advanced Research Projects Agency's autonomous vehicle race. Two years later, Google hired Thrun. And in 2010 Thrun's group unveiled Google's car.

Why the sudden change? Maybe it had to do with the ongoing drop in the cost of radar, infrared imagers, sonar, GPS, and other sensors. Or maybe it was the dramatic improvement in the processing power of embedded systems. Or it could be that engineers had just gotten comfortable with such building-block technologies as adaptive cruise control, automatic parking, and navigation.

In any case, by the beginning of this decade every major automaker was working on autonomous driving. The most in-your-face firm, as usual, is Nissan Motor Co., whose chief executive, Carlos Ghosn, recently promised to introduce not one car but a line of cars that can drive themselves–by 2020. Big talk, you may say, but in 2007 Ghosn vowed to deliver the all-electric Leaf by 2010, and he did.

Interesting, also, is Volvo's growing investment in autonomous driving technology. As part of the European research project known as SARTRE (Social Attitudes to Road Traffic Risk in Europe), the final version of which ran from 2009 to 2012,

Learning to Think

Sixty-five years of automotive baby steps

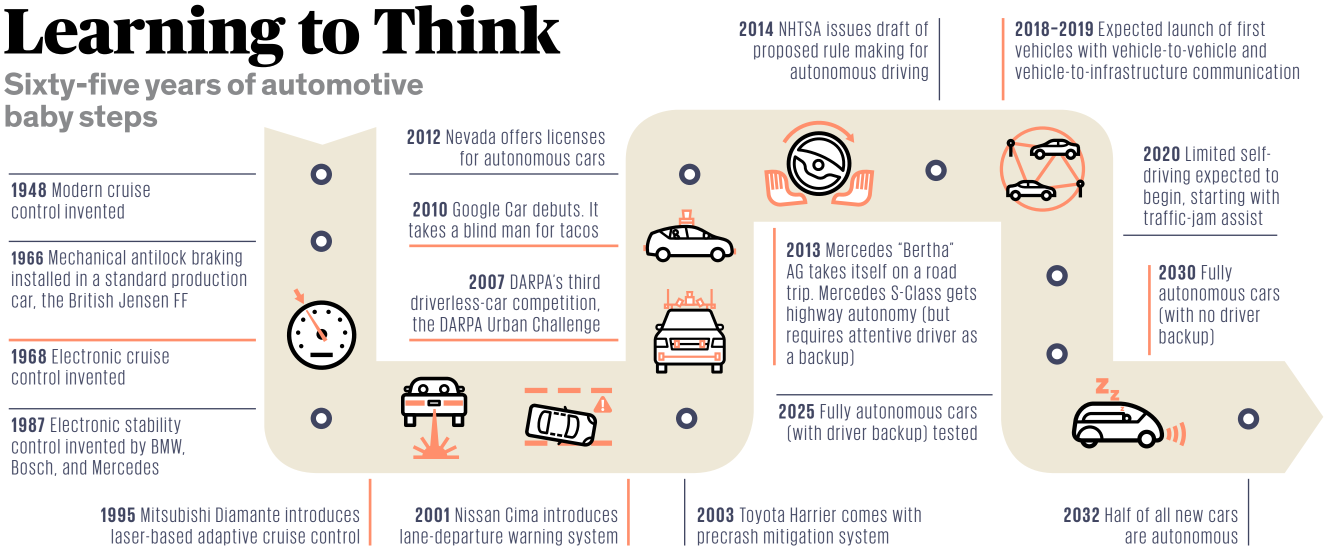


ILLUSTRATION BY James Provost

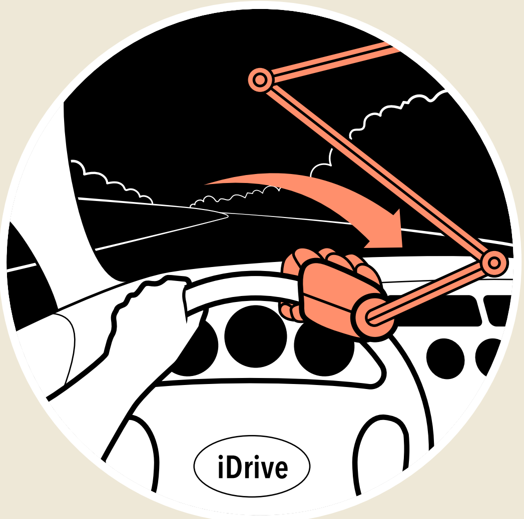
Volvo supplied cars that automatically followed in a line behind a truck driven by a professional driver, saving effort and fuel.

A lead engineer in that project, Erik Coelingh, says Volvo is using a fleet of 100 cars to test out autonomy in the Swedish city of Gothenburg. Such validation will take time, he adds, no matter how fast other technologies may advance. "Even if you've tested the system in 10 cars and it works fine, with not a single incident, it doesn't tell you a lot about how 100 000 cars will do on the road."

He sees the technology advancing by degrees, beginning in test-bed cities like Gothenburg and in places where pedestrians aren't allowed–say, within mines in Australia, where huge robotrucks are already carrying ore. Next come traffic jams, where movement is slow and there is no oncoming traffic. Then, he says, come selected routes, every meter of which has been carefully validated, so that a driver can just "punch a button to drive autonomously."

Testing will proceed road by road and city by city, Coelingh says, building to the point at which cars can plan the route and take you there, from door to door. But he figures it'll be 10 years for the first commercial robocars (that's three more years than Ghosn predicts), and 20 before they take up a big share of new sales. However, he allows, autonomy could come faster in places where much of the infrastructure is only now being put in, like China. (By the way, Volvo is now owned by Geely Automobile, a Chinese firm.)

Where infrastructure is designed with robocars in mind, many of the hardest problems will be easy to solve. Cars will talk to the road, to the traffic signs, and to one another. What one car up ahead can see, all will know about. Even the problem of identifying pedestrians lurking behind shrubbery will finally fade away: After all, if cars can talk to signs, they can certainly talk to the cellphone in your pocket. Traffic | CONTINUED ON PAGE 80



WHAT COULD POSSIBLY GO WRONG?

When 99% Safe Isn't Safe Enough

The dangers of autonomous-drive technology arise just as it approaches perfection

The worst thing that will accompany the march of robocar technology will come when cars are almost but not quite autonomous. Their prowess will lull all-too-human drivers into complacency.

"Automating the vehicle is a long continuum," says Josh Switkes, founder and chairman of Peloton Technology, which is working on automating trucks. "If the driver doesn't do anything most of the time but still has to do emergency braking? That's not good. He doesn't pay attention—he's not there when you need him."

To stop that from happening, this year's Mercedes S-Class car actually sounds an alarm if the driver's hand leaves the wheel for more than 10 seconds. Expect such backseat driving to get worse as self-driving technology gets better.

A second problem will be the eye-catching nature of the few accidents that do happen when cars routinely speed along with a 2-meter gap between them. In that world, anything that goes wrong for one car will go wrong for a lot of cars, and nobody will heed those who cite the statistics showing that driving is safer than walking. We know this will happen because it already has—for air travel.

There will be other little problems. The early robocars will be tuned to "extra polite," allowing aggressive human drivers to practically run them off the road. Lawyers will have a field day when something goes wrong. And the very connectedness of cars—to one another and to the roads and signage—will take away the anonymity of the passengers. You'll never drive alone—even if you want to.

Even the cities, relieved of most of their burden of cars, will also miss the revenue from parking fees. And public-transit systems, like subways, will suffer for lack of business.

But really, the worst single thing that could happen is that the autonomous car might not happen fast enough—not until the very end of the forecasting horizon of this special issue of *IEEE Spectrum*.

"Really automatic, as for a blind driver? Fifty years," says Jens Desens, a Daimler engineer who works on his company's experimental autonomous car and ought to know. He waves both hands for emphasis, which he can do because the car is doing all the driving.

We're outside Stuttgart, cruising along an autobahn in a Mercedes S-Class tricked out with extra sensors. Unlike the experimental version, it can't handle city streets, but it sure knows how to pass a slowpoke on a highway.

"Come on," I sputter, after just such a demonstration. "If this car can do this now, what won't it be able to do in a decade?"

Desens sits back, his hands in his lap (of course), and sighs.

"Look, we started in the '60s and '70s last century to develop this radar," he says with another sigh. "It was this big"—his hands spread way out again—"like three suitcases. We started to sell it only in 1999. So 25 years of development just for the radar sensor." *—P.E.R.*

ILLUSTRATION BY MCKIBILLO

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

POSTCARDS FROM 2064

As I See It

I, for one, welcome our robot overlords

Photography by **Dan Saelinger**

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

PROP STYLING BY **Dominique Baynes**; CGI BY **Swell**

WEARABLE

THE FUTURE WE DESERVE

BEYOND WORDS

Wearable computers will let us share thoughts and sensations

By **Ariel Bleicher**

IN AUGUST OF 1961, FABLED MATHEMATICIANS EDWARD O. Thorp and Claude Shannon, of MIT, walked into a Las Vegas casino. They intended to try their luck at roulette, a game in which players bet on where a whirling ball will land after falling from an outer stationary track onto an inner spinning wheel. But they weren't typical gamblers. • They worked as a team. Shannon watched the wheel, clandestinely clocking the speeds of the rotor and the ball by flipping microswitches in his shoe with his big toe. The signals coursed through wires that ran up his pant leg to a small computer strapped to his waist. The machine calculated the ball's final resting position and then transmitted this prediction wirelessly to a receiver under Thorp's shirt. Through a tiny speaker in his ear, Thorp heard one of eight distinct tones that advised him

PHOTOGRAPH BY Adam Voorhes


COMFORT
LOVE :-)
CLOSE
LOOK
NICE WARM
120 BPM
HUNGRY
75F @
POSITIVE
SHINY
10:00AM
BLUE SKY
20/20
SAY
AGREE
SHINY
EAST
WOW
HEALTHY
ITCHY
WHAT
LOOK
BIRD
MEETING
WORD
@ CLOSE
LOUD
5 MILES
SAY

on how to bet. To his and Shannon's delight, he reported years later, this newfound faculty increased the duo's odds of winning by 44 percent, and they "often turned a few dimes into a pile."

Engineers widely regard this invention as the first wearable computer–an early glimpse at today's fitness trackers, smart watches, and augmented-reality eyewear, and their possible descendants: electronic contact lenses, haptic undergarments, brain-reading caps, body-monitoring tattoos, gesture-recognizing rings, speech-detecting tongue piercings, and touch-sensitive sleeves, pleats, buttons, and zippers. Compared with today's powerful all-purpose processors, the MIT mathematicians' machine wasn't much–just 12 transistors hand-soldered in an analog circuit. Yet the impact on its wearers was profound–foretelling, perhaps, a future when we depend on our electronic devices to experience life as much as we rely on our eyes, ears, and skin.

"We will get to a point when we stop thinking of technologies as external to our bodies," says Desney Tan, an expert in computer interfaces at Microsoft Research, in Redmond, Wash. Wearables will always be on and immediately accessible. Donning them, he forecasts, will allow us to "sense and capture many more things about the world" and to communicate those sensations in new ways. For example, on-body displays could let people use images to express ideas in face-to-face conversations. Brain-activity monitors could capture emotions and add them automatically to text messages. Haptic fabrics could let a father-to-be experience the kicking of his unborn baby.

Electric circuits are creeping ever closer to us–from our desktops to our laps, our pockets, and now our faces and wrists. And many engineers predict the trend will continue: In the coming decades, computers will be seamlessly woven into our clothing, fashioned into our jewelry, and painted on our skin. Eventually, we may not be able to distinguish their capabilities from our own.

TOUCHABLES: Carnegie Mellon's Chris Harrison demonstrates Touch Tools, an app he built to explore new ways of interacting with screens. In the future, he says, distinct hand gestures could replace traditional toolbars.

ELECTRONIC COMMUNICATION HAS long been limited not by computing power but by the ability of machines to understand us. The human and the computer possess "enormously powerful information-processing capabilities," wrote Edward Tufte, a data-visualization pioneer now at Yale University, in 1989. "Yet communication between the two must pass through the low-resolution, low-information, narrow-band user interface of a video display terminal." Your phone, in other words, may be able to send a message in a split second, but you can type only so fast.

At first glance, it seems the problem gets worse with wearables. "We can put a really powerful computer in a smart watch, or into Google Glass, or whatever the next form factor will be," says Chris Harrison, an assistant professor of human-computer interaction at Carnegie Mellon University, in Pittsburgh. "So the question is, How do you get input into something so small?"

In the coming era of wearable computing, as Harrison foresees it, we will manipulate digital bits the same way we do real objects–with our hands. "Touch is a really powerful, wonderfully intuitive thing," he says, adding that although the touch screens on today's smartphones, tablets, and watches are a step in the right direction, "they're pretty lame." The gestures they recognize are disappointingly few, including one- and multifinger taps, swipes, and pinches. "We don't do things in the real world based on the number of fingers we poke at things," he quips. "There are all these other, really rich dimensions of touch that touch screens ignore"–such as pressure, contact area, the shape of your hand, and whether you use a pad, knuckle, or nail.

To explore more diverse types of virtual touch, Harrison does what he calls "time-machine research." In a bright, airy laboratory that he has adorned with obsolete PCs and hand-welded sculptures made of discarded cameras and cellphones, he and his students build prototypes of possible future interfaces by hacking or cobbling together existing technologies. From a table cluttered with to-go cups, cables, laptops, watch parts, and mannequin hands, he produces an iPad.

"Think about the natural ways you use your hands," he begins as he launches a homespun app called Touch Tools. "Grasps, for example, are really iconic. How I hold a pen is very different from how I hold a dry eraser." Pinching his middle and index fingers and thumb together as if clutching an invisible stylus, he touches the screen with his fingertips. The gesture brings up an image of a ballpoint pen, which he uses to draw a doodle. He then widens his grip

PREVIOUS PAGE: PROP STYLIST: ROBIN FINLAY; THIS PAGE: CARNEGIE MELLON UNIVERSITY (3) about an inch, summoning a pink rubber eraser. He erases his scribble. "So I don't need tool bars–I just change the shape of my hand," he says. He conjures a tape measure, using his other hand to extend the tape. Then comes a magnifying glass, a mouse, a camera.

You might think that touch gestures won't be very useful when people stop carrying around screens and sleek wee wearables become the norm. Not so. "If we're clever about how we use our fingers, we can actually make interactions on even something as small as a smart watch really quite powerful," Harrison says. With Gierad Laput, a Ph.D. student, he has built a smart watch that users can manipulate mechanically. Four rice-grain-size sensors, which click and pivot like miniature joysticks, detect when you shift, tilt, twist, or depress the face, providing "all these different degrees of freedom that let you interact with the watch in more expressive ways than just using a touch screen," Laput says. To allow for more expansive interactions, he suggests, future engineers could put light projectors into watches or other wearables such as lapel pins, which would let people use the space around these devices.

"Could you turn your skin into a touch screen?" Harrison interjects. "Could you turn this wall?"

As if on cue, Ph.D. student Robert Xiao presents a textbook-size box on a tripod. The contraption, called WorldKit, contains a digital projector and a Microsoft Kinect depth camera wired to a laptop. Working with Harrison and computer-science professor Scott Hudson, Xiao programmed the system to "explode information on every surface of the environment," he explains. He swipes his palm across the wall, triggering a soft yellow glow that trails his hand. "When I lift my hand up, it's actually a multi-touch surface."

"We're painting interfaces onto the world," Harrison says. "I could say, 'I want a thermostat here and a calendar there,' or 'I want this whole wall to be blue.' "

WHAT COULD POSSIBLY GO WRONG?

Your Body, Broadcasting Live

Wearable sensors could spill your innermost secrets

It's already an all-too-familiar fear. You buy a smart gizmo or download an Internet app in hopes it will entertain you or make you healthier or your life easier. But then you wonder: Are criminals hacking my accounts? Are companies profiting from a knowledge of my habits? Is the government collecting my texts and e-mails?

And if you fret about the fate of data being gathered by the smartphone in your pocket, you'll shudder at the thought of what could leak from hardware in your clothes or on your skin. Wearables will likely record not just what you do and whom you talk to but also the states of your mind and body, including your heart rate, blood pressure, and brain activity—information you probably don't want shared too widely. What if your boss could measure how focused you are at work? What if your spouse could know whom else you found attractive?

Without reliable security, clear privacy laws, and simple user controls, the wearables generations might have few secrets left to keep. People might give up data unwittingly, lured by cheap deals and ignorant of the fine print of privacy policies, says Jason Hong, a privacy and security expert at Carnegie Mellon. Smartphone users, he points out, are often surprised that many free apps keep close tabs on them. He fingers a few notorious snoops: the game *Angry Birds*, Bible App, and Brightest Flashlight Free. "People don't expect these apps to collect location data," he says, but they do. "They send it out to advertisers."

Records from wearables such as brain sensors could also be used in criminal investigations, says Nita Farahany, who studies the legal implications of emerging technologies at Duke University, in Durham, N.C. Under U.S. law, she explains, "you can't be forced to testify against yourself, but that doesn't mean your body can't be used against you." If prosecutors can use fingerprints and DNA to get a conviction, what's to stop them from using scans of a suspect's thoughts or emotional reactions?

The most vexing spies, however, may be wearers themselves. Wearables could allow you to watch yourself so closely that you will stop just being you. "Say I go out to dinner, and I have a great time," imagines Stephen Fairclough, a psychophysiologist at Liverpool John Moores University, in England. "Then I get home and my smart watch tells me I was stressed. I think, 'Was I?' I start second-guessing myself, and it changes the way I perceive the experience." If people rely too readily on computerized data to analyze their behavior and make sense of the world, he worries, "we may stop trusting our own instincts and our own feelings."

Many engineers believe that the technical challenges of building tiny wearable machines will be easily overcome. "The last 50 years have been about evolving technology," says Desney Tan at Microsoft Research, referring to developments in electronics that could one day allow wearables to vastly extend the abilities of *Homo technologicus*. "The next 50 will be about inventing the human being."

So let's make sure we get it right. *—A.B.*

ILLUSTRATION BY MCKIBILLO

MIND-READING MACHINE: A volunteer tests a brain-computer interface being developed at the U.S. Army Research Laboratory. The system can identify when a user spots a potential threat, such as a person with a gun, simply by observing brain activity.

RON CARTY/U.S. ARMY RESEARCH LABORATORY

"You want a light switch?" Xiao asks, and one appears next to Harrison's office door. "We actually had this controlling the lights." Xiao envisions a future in which disc jockeys queue tracks on their forearms and architects revise blueprints on the walls of their clients' homes. "In 20 years, maybe people will go to Home Depot and instead of buying lightbulbs, they'll be buying information bulbs."

In fact, future consumers may choose from many different kinds of interfaces, mixing and matching to satisfy their style and fancy. Other researchers are now investigating smart glasses that track eye movements, wristbands that capture hand gestures, tongue implants that recognize whispers, even neck tattoos that pick up subvocalizations–the subtle vibrations your throat muscles make when you imagine how a word sounds.

At the Georgia Institute of Technology, in Atlanta, Clint Zeagler is designing interfaces for smart clothing, such as embroidered patterns sewn with conductive thread, that users can navigate by touch rather than sight. "Why can't my zipper be a scroll?" he asks. "Why can't my button for my pants be a button? Why can't it turn on my pants?"

THE GADGETS WE'LL WEAR WON'T just be handier than those we now have to carry. Wearables will be truly revolutionary, some experts say, because they'll learn things about us that we never tell them or that we might not think to find out for ourselves.

The seeds of such a future are already here. Google's digital personal assistant, Now, has the smarts to figure out the locations of your home and workplace just by tracking your movements during the day. Because it knows this information, it can, for instance, display on its own initiative traffic updates on your phone 5 minutes before you begin your commute.

In February, Yahoo announced a five-year US $10 million partnership with Carnegie Mellon to create the "next next-generation personal assistant," says Justine Cassell, a computer-science professor and codirector of the project. The software sidekick she has in mind "will constantly be learning about you and becoming more personalized." It will know–*without your input*–what cuisines you like, who your friends are, and that you might enjoy that new shop across the street.

Your phone already collects a good deal of intelligence on you–through your GPS trail, browsing history, texts, calendars, e-mails, and online social networks. But wearables will be able to gather much more. Sensors exist or are in the works that can observe your breath, sweat, gaze, facial expressions, heart rate, muscle movements, and sleep patterns, as well as the ambient temperature and air quality. And now scientists are starting to develop wearable technologies that can eavesdrop on the brain.

Known as brain-computer interfaces, or BCIs, these systems are found mostly in research laboratories. They tend to be bulky and uncomfortable, and the information they can extract from the brain is still crude. The most common approach is called electroencephalography, or EEG. A typical setup consists of a headband or cap lined with anywhere from a few to a few hundred electrodes, which measure voltage fluctuations produced by electrically active brain cells, or neurons. By the time these signals reach the scalp, however, they are weak, jumbled, and incomplete, making it difficult to pick out subtle events, such as thoughts or emotions, from the noise made by other brain processes, facial movements, and nearby electronics.

TIME CAPSULE: 1964

BASIC COMPUTER LANGUAGE

Two Dartmouth professors, John Kemeny and Thomas Kurtz, and a team of undergraduate students developed the BASIC computer language in 1964. During the mid-1970s, Bill Gates and Paul Allen catapulted BASIC's popularity when they wrote a version of the language for the MITS Altair 8800.

PHOTO-ILLUSTRATION BY Gluekit

But engineers are beginning to overcome these challenges. Using machine-learning techniques, they have trained computers to recognize certain general states of mind from EEG recordings, including attention, arousal, fatigue, stress, and cognitive load. Early prototype BCIs can also detect when a person decides to act, identifies something he or she is looking for, or becomes fully focused on a task–a mental state known as flow or "in the zone." Their inventors are confident that these technologies will be commonplace.

"Say you're walking down the street," imagines Paul Sajda, a BCI expert at Columbia University, in New York City. "You've got your Google Glass on, with EEG sensors embedded in the frames." You notice things–a pretty bird, a flashy car–and your future Glass notices you noticing. If it also tracks your gaze, it can identify what you're looking at. Maybe your Glass tells you something useful–the species of that bird, the make of that car. Maybe it takes a picture. "A very simple app might be a stuff-I-thought-was-interesting-today scrapbook," Sajda proposes.

"Your computer will act as an extension of your own mind"

FOR MANY RESEARCHERS WHO WORK in wearable computing, the ultimate goal is to design machines that use data from the brain and body to understand the world in human terms. For example, Kaleb McDowell and Brent Lance at the U.S. Army Research Laboratory, in Aberdeen, Md., and their colleagues are developing a BCI that categorizes images based on how a person's brain responds to them.

In the system's current iteration, a volunteer wears a cap studded with 64 electrodes while watching a series of scenes–buildings, streets, fields. She is told to look for threats, such as people with guns. At five images per second, the pictures flash by too fast for her to react physically to each one, even to press a button. All the while, the BCI monitors electrical pulses from her brain, and when it sees signals suggesting she has spotted a shooter, it tags those images "threat." The scientists have found that the computer identifies these targets correctly at least 85 percent of the time.

In just a few years, McDowell and Lance speculate, BCIs could be used commercially to train computer-vision systems or help military analysts sift through aerial footage from satellites and drones. In a few decades? Okay, we'll dream big, they say: Brain-sensing and brain-modeling technologies will advance enough to be able to observe emotions, desires, and comprehension. Other researchers fantasize that BCIs might someday record perceptions, dreams, and maybe even internal speech–the voice you hear in your head when you talk to yourself.

In the future, people will wear BCIs constantly while also sporting cameras, microphones, and other sensors that will simultaneously record everything they see, hear, and feel. The network of computers on a person's body will then use these data to build digital representations of how he or she perceives the world. For instance, your wearables might track every gesture that calms you, every sound that surprises you, every remark that makes you swear under your breath. Over time, these machines will learn to anticipate your actions and emotions and will automatically tailor your environment to suit your needs–muting your alerts when you're in an important meeting, dimming the lights when you drift off to sleep. They may even recognize subtle cues you don't notice or can't sense, such as early signs of depression or the onset of a migraine.

And when our computers know us better than we know ourselves, they will help us to communicate better with one another. They will monitor our conversations and inform us when others are bored, inspired, hurt, grateful, or just not on the same page. They will encourage us to speak up when we are shy, stop us from sending e-mails when we are angry, and remind us of what makes us happier when we are sad.

Thad Starner, a professor at Georgia Tech and a technical lead for Google Glass, has worn some version of a computerized head-up display for 21 years. He uses a one-handed keyboard to take notes and browse the Web. One day, he's sure, he will no longer need to search for pertinent information because his Glass will listen to his conversations and intuitively fetch the data for him. It will appear before his eyes as quickly and unobtrusively as if he were recalling a memory. "Your computer will act as an extension of your own mind," he prophesies.

Sooner or later, our electronic gizmos will no longer be possessions we take or leave behind. They will be us. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/mobile0614

WHAT COULD GO RIGHT?

Download, Practice, Done

Wearables could help you learn new skills with superhuman speed

THE GLOVE LOOKS humdrum, like a garment you might pick up at a sporting-goods store. It's made of soft black leather and fingerless, like a cyclist's or weight lifter's glove. The similarity is, however, deceiving.

"I have a glove that can teach you how to play a piano melody," Thad Starner declares when I call to chat about the future of wearable computing. Now a professor at the Georgia Institute of Technology and a technical lead of Google Glass, he helped pioneer the field in the 1990s as a student at MIT. "During this conversation, you could have learned 'Amazing Grace.' "

"Really?" I say. "While we're talking?"

"Sure," he says and invites me to Atlanta to see for myself.

Caitlyn Seim, a Ph.D student, slips the glove onto my hand. Inside each of the five finger holes she has sewn a flat vibration motor. The five tiny vibrators, which perch atop my digits like gemstones on rings, are wired to a microcontroller on the back of my hand. Seim has programmed it to fire the motors in the same sequence that my fingers would strike keys on a piano.

But she doesn't tell me which tune I'll be learning. "You'll just feel a little buzzing," she says, flipping on the electronics. Then Starner whisks me away to show off his lab's myriad other projects:

GEORGIA TECH

a language-translation app for Glass, a magnetic tongue implant for voicing silent commands to a computer, a smart vest to help divers communicate with dolphins, smart chew toys to help police dogs communicate with handlers, and all manner of other wonderfully wacky wearables.

Once every minute for the next 2 hours, the motors in the glove vibrate across my fingers. I try to figure out the pattern: buzz...*middle finger*...buzz...*ring fin*...buzz... buzz...*ger*...buzz...*uh*...buzz...buzz...*crap*. "IMPOSSIBLE," I write in my notebook.

At last, Starner escorts me to a keyboard. He plays the first passage of a song—15 notes that the glove has supposedly taught me. I recognize the tune. It's Beethoven's "Ode to Joy." I take off the glove.

"Start here," Starner says, hitting the first note. I lay my fingers on the keys. *Middle finger*...*middle finger*...*ring finger*... "I don't know," I say, embarrassed.

"Don't think about it," Starner says.

I start again. *Middle*...*middle*...*ring*... *pinky*...*pinky*...*ring*...*middle*...*pointer*.... "This is crazy!" I say, still playing. And I don't stop. I finish the first passage, then play the second, and start into the third.

"Now, hold on!" Starner interjects. "Have you played this before?"

"Never," I say. It's true—I never took piano lessons. Befuddled, he inspects the glove and discovers it's been programmed to vibrate all four phrases of the song—61 notes, not 15. Typically, he explains, he and his students teach only one phrase at a time. I approach the keyboard again. I fumble a few tries—I'm learning, after all—but within minutes, I can play the melody perfectly. I feel giddy, like I've just discovered an innate talent I never knew I had.

"You just know what to do—it's insane," Seim notes. She recently taught herself to play "Ode to Joy" by wearing the glove while writing an application for a research grant. "It's almost like watching a phantom hand."

Starner and his colleagues believe that the repeated buzzing from the glove creates a muscle memory that enables a wearer to learn to play a song with far less practice than it would take without haptic stimulation. They have also studied the glove's effect on people with spinal cord injuries and found that it can help them regain some sensation and dexterity in their hands. Most recently, the researchers have shown that wearing haptic gloves while doing other tasks can speed up the process of learning to type and read braille—evidence that the technology could impart not just patterns but also language.

"We don't know the limits," Starner says. "Can we put these sorts of vibration motors on people's legs and teach them how to dance? Can we teach people how to throw a better baseball?" He mentions a scene from the sci-fi thriller *The Matrix* in which the film's heroes, Neo and Trinity, hijack a helicopter: "Can you fly that thing?" Neo asks his right-hand woman. "Not *yet*," Trinity says. Her eyelids flicker as the knowledge pours through a data port at the back of her skull. Seconds later they're in the air.

"Of course you can't do *that*," I say.

Starner grins. "Not *yet*." *–A.B.*

ROBOTS

THE FUTURE WE DESERVE

SO, WHERE ARE MY ROBOT SERVANTS?

Tomorrow's robots will become true helpers and companions in people's homes

By **Erico Guizzo**

FOUR YEARS AGO, RESEARCHERS AT THE UNIVERSITY OF California, Berkeley, uploaded a video to YouTube. It featured a demonstration they'd done using a powerful new robot called PR2, a dishwasher-size machine with two hefty arms and six camera eyes on its face. In the demo, PR2 stands before a disorderly pile of small towels. Then, slowly but surely, it stretches its arms, picks up a towel, and neatly folds it, even patting it gently to smooth out the wrinkles. The robot repeats the routine until no more towels are left in the heap. • The researchers were pleased with their work, but they didn't quite expect what came next: Their video went viral. Within days, hundreds of thousands of people watched it as news of the robot spread through social media and the blogosphere. Reports popped up on newscasts and publications around the

ILLUSTRATION BY Ben Wiseman

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®


1099

world. One Twitter user humorously summed up what the achievement might portend: "I, for one, welcome our towel-folding robot overlords."

This robotic laundry experiment had obviously struck a nerve. The idea of robots doing chores around the house has long captured people's imaginations. For some, robots would mean freedom from tasks they don't have time for or don't want to do. For others, robots would mean even more: They would help them live independently longer, providing care and perhaps even some degree of companionship.

It's disappointing, then, that other than robotic toys and vacuum cleaners, robots are a rare sight in our homes today. And yet, here we are, still eagerly waiting for this technology to blossom. So, where are the robot servants?

Some recent developments suggest that they might not be too far away. Processors, sensors, and other components that robots need have gotten much better and cheaper, propelled by advances in smartphone technology. And open-source software is now available for robot simulation, control, vision, and many other functions. Also, rapid-prototyping tools like 3-D printers and laser cutters are lowering the barriers for designing and building new robots.

The result is that interest in robotics is exploding among researchers, hobbyists, and entrepreneurs. Robot-related start-ups and crowdfunded projects are proliferating. Venture capitalists have taken notice of this trend–and so have tech giants like Amazon.com and Google, both of which seem to have big plans for robots.

Now, where this is all leading is hard to tell. Some skeptics predict that in 20 or 30 years, personal domestic robots will still be just laboratory playthings. Others believe that in that same time frame intelligent machines will routinely be providing household help, advice, and company. Then, of course, there are the countless possibilities in between.

We editors at *IEEE Spectrum* don't pretend to know how things will unfold, but of all the scenarios we're able to envision, there's one in particular we find not only possible but *desirable*. It's one in which personal robots won't be exclusive, expensive offerings few can afford. Rather, they'll be as commonplace as computers or mobile phones are today, and their development will provide a global engine for innovation and prosperity.

ROBOT EVOLUTION: PR2 [left] sold for US $400 000; one of its successors, UBR-1, is a bit less capable but costs about one-tenth as much.

LEFT: WILLOW GARAGE; RIGHT: UNBOUNDED ROBOTICS

So allow us to expand on our upbeat vision.

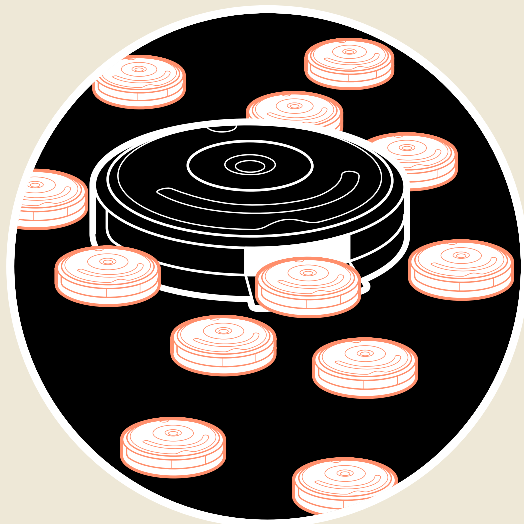
The domestic robots of tomorrow will be a varied bunch. Many will be small, single-task machines that'll clean floors, water plants, feed pets, and such. They'll hide most of the time, and we won't pay much attention to them. Think of them as smart, mobile versions of today's household appliances.

The robots that will really change things will be bigger and more powerful, and they will perform multiple tasks for us. They'll have wheels or tracks, and some may sport legs. They'll certainly have manipulator arms to handle objects. As with any piece of technology, you'll be able to choose among many models with different styles, capabilities, and prices. But the key thing they'll have in common is how they learn to do what they do.

These robots won't do everything right out of the box. Instead, these general-purpose programmable platforms will start by doing just a few simple tasks, and they'll continually acquire new capabilities. They'll come equipped with attachment points for new accessories and, more important, standard interfaces that allow new third-party software to add functions to the robots' repertoire that their manufacturers never imagined, much like the apps we install on our phones.

It's a scenario that, in one form or another, some roboticists already have in sight. "While a computer program is pure software, some robot apps will be a combination of software and hardware," says Colin Angle, chief executive and cofounder of iRobot Corp., an industry leader based in Bedford, Mass. "These apps will include not only software but maybe also files that people can use in their 3-D printers to make parts at home."

What will the apps and accessories allow this new generation of home robots to do? Anything and everything, we hope. Some possibilities that immediately come to mind: Robots will learn



WHAT COULD POSSIBLY GO WRONG?

No Joy in Robots

When Bill Joy saw the robopocalypse

When it comes to evil robots, Hollywood has come up with nearly every scary scenario imaginable. Robots revolting against humanity, android killers on the loose, machines harvesting energy from humans—these are some of the themes that have appeared in movies like *Terminator*; *Blade Runner*; *Metropolis*; *The Matrix*; *I, Robot*; *Minority Report*; *2001: A Space Odyssey*; *Westworld*; and *RoboCop*. Steven Spielberg even has a movie called *Robopocalypse* in the works.

Although many of these scenarios are frightening and gruesome, what is perhaps one of the darkest and most disturbing views of tomorrow's robots didn't come from a movie script: It came from an essay written by influential computer architect and Internet pioneer Bill Joy, cofounder of Sun Microsystems. In 2000, Joy wrote the *Wired* cover story "Why the Future Doesn't Need Us," arguing that three fast-changing technologies—robotics, genetic engineering, and nanotechnology—were "threatening to make humans an endangered species."

In the essay, he explained that these technologies pose a real threat because they could run amok and unleash an uncontrolled process of self-replication. For robotics, in particular, he worried about the possibility of intelligent machines evolving into a "superior robot species": "How soon could such an intelligent robot be built? The coming advances in computing power seem to make it possible by 2030. And once an intelligent robot exists, it is only a small step to a robot species—to an intelligent robot that can make evolved copies of itself."

The result of self-replicating robots, Joy wrote, could mean machines competing for resources with us, or worse, our extermination. He described similarly gloomy scenarios involving genetically engineered pathogens and self-cloning nanostructures wrecking everything in their paths, creations destroying their creators—us.

Faced with what he saw as a real threat to our existence, and disappointed that technologists weren't taking responsibility for their potentially humanity-annihilating inventions, Joy saw no alternative: He argued that we should relinquish the development of certain technologies and limit our pursuit of some kinds of knowledge.

Joy is a respected techno guru—he helped create one flavor of Unix, Java, and Sun workstations and servers—so people paid attention. His essay sparked a heated debate. Some thanked Joy for pointing out the dangers of these accelerating technologies. Others called him a neo-Luddite and criticized him for quoting the writings of Ted Kaczynski, the Unabomber, and for not suggesting more concrete solutions. Another influential tech visionary, Ray Kurzweil, whose own predictions were among the things that led Joy to write his essay, rejected his call for curbing broad areas of technology and suggested we adopt ethical guidelines and more oversight.

It's now 14 years later. If we look at the dangers Joy warned about in his essay, we don't think the latest technological advances have brought us any closer to the doomsday scenarios he feared. Unless our Roombas are about to stage an uprising, we don't think we'll be seeing a self-reproducing superior robot species anytime soon—except in the movies. —*E.G.*

ILLUSTRATION BY MCKIBILLO

[redacted]

to fetch things from the fridge, operate the microwave, clear the table after meals, load and unload the dishwasher, answer the door, pick up toys from the floor, clean toilets, and of course, do laundry. A free app will let your robot find all the socks in the bin; a paid version will find, pair, and place them in your drawer. The app may require that you 3-D print a new accessory—a sock-friendly gripper, say—or get it sent to your home. (Yes, people still receive packages in the future, perhaps delivered by Amazon drones.)

For this to come about, companies making domestic robots will have to give up control in the name of openness. How soon that will happen is unclear, though. A big impediment, argues Ryan Calo, a professor of law at the University of Washington, is the possible legal liability such openness would engender. People have come to expect their personal computers to sometimes act a bit buggy with third-party software, and as a consequence lawsuits are rare. But if personal robots ever went haywire, it's likely that their owners would sue the manufacturer for damages.

Calo thinks that some tweaks to the law could balance the danger of making robotic platforms open against the great promise of this approach. One reason to want to see things evolve this way is that creating a capable domestic robot will probably be too hard for a single company to figure out by itself. The robot makers that will prevail will be the ones that allow others to expand and enhance their creations. The same was true for personal-computer manufacturers decades ago, and this paradigm reigns today in the mobile world, with Apple's iOS and Google's Android running apps from all over.

So expect standard platforms to take hold in robotics, too. New apps and accessories for them will then gush from a vast number of companies and individuals—be it a kid in a garage in Silicon Valley, a group of programmers in Finland, or skilled engineers in India or Brazil. And as personal robots are opened up to the world, they'll become the next transformative technology after the PC, the Internet, and the smartphone.

OUR DESIRED SCENARIO WILL COME to pass only if technologists solve some key challenges. To appreciate what they're facing, it might help to understand what a state-of-the-art, general-purpose robotic platform looks like today. For that, consider our towel-folding robot, PR2.

Built by a team of robot wizards at a company called Willow Garage, in Menlo Park, Calif., PR2 is a mechanical marvel, possibly the most capable research robot ever built. Willow engineers have programmed the robot to grab drinks from a fridge, play pool, and plug itself in for recharging. Other research groups have taught it to bake cookies, prepare a traditional Bavarian breakfast, and even venture out of the lab to go buy sandwiches.

As impressive as these demonstrations are, PR2 also underscores the current limitations of robotics. The robot is awkwardly big. It can't maneuver in tight spaces, and, weighing 220 kilograms, it could do some real damage if it crashed into something or someone. Another problem is that it does things slowly. In the Berkeley towel-folding demo, PR2 took 25 minutes to fold each towel (the researchers had to speed up their video dramatically to make it watchable). And then there's the price tag: Each PR2 costs a whopping US $400 000.

But again, look at what happened in the computer industry: While mainframes sold for hundreds of thousands of dollars in the 1960s and '70s, the first IBM PC, introduced in 1981, cost about $4000 in today's dollars. So if we peer into the future, we can easily imagine a smaller, smarter, and cheaper successor to PR2 becoming a universal robotic platform that costs about as much as a typical car, perhaps less. What would it take to build such a machine?

Thanks to Moore's Law, the computers and sensors used in robots are advancing at a formidable pace. High-resolution cameras, inertial measurement units, laser range finders, and 3-D depth sensors like Microsoft's Kinect have profoundly changed robotics in the past half decade. One hardware component, however, has been holding robots back: their actuators. These are essentially electric motors connected to gears or other mechanisms. In a robot like PR2, they power its wheels and arms. The problem is that the actuators in robots today tend to be bulky and costly, and as a result those robots are big and expensive. (PR2's arms alone accounted for about half of the robot's hardware costs.)

Researchers are experimenting with alternatives, including bioinspired artificial muscles, cable-driven manipulators, and even soft, inflatable arms. Another possibility is building actuators that replace most metal parts with carbon fiber, plastics, and other lightweight materials.

"For me a big unknown is the ways in which new materials will change what we can put in robots," says Rodney Brooks, the celebrated roboticist and founder of Rethink Robotics in Boston. He's hope-

TIME CAPSULE: 1964

SHARP COMPET CS-10A

After four years of development, Sharp Corp. introduced the Compet CS-10A desktop calculator in 1964. It was the first transistorized calculator produced by a Japanese manufacturer. It cost 535 000 yen, about the same as a subcompact car in Japan at the time.

PHOTO-ILLUSTRATION BY Gluekit

ful, though, that materials scientists will indeed have a lot to offer robotics.

Reducing size and weight will be critical in making tomorrow's personal robots nimbler, safer, and cheaper. But some say an even greater challenge will be software. "Like the early PCs, you need hardware of basic capabilities, but for the most part the industry did not really accelerate until you had great software," says Tandy Trower, founder of Hoaloha Robotics, a Seattle-based start-up developing robots to assist the elderly.

The problem with the software today is that roboticists spend too much time reinventing the wheel, each creating different modules to handle control, communication, and other basic tasks in the robots. This, in part, is necessary because robots are still highly customized machines, and so reusing code is difficult or impossible.

> "A robot to keep me company, I think that's something we will see"

But it's hard to see personal robots flourishing until large numbers of different manufacturers' machines are equipped with standardized components and interfaces. This, in turn, will make programming them–and sharing code–easier. And indeed, some robotics software is already moving in this direction.

Consider again Willow Garage's PR2. Its software foundation is called the Robot Operating System, or ROS, which takes care of all the basic functionalities of the robot, such as making sure sensors and computers are talking to one another and much more. ROS is also integrated with a set of libraries that programmers can use to make the robot perform tasks that involve simulation, 3-D data processing, computer vision, and other things. That means they can develop complex applications–such as folding towels–without worrying about low-level details like how to acquire data from a sensor or keep track of where different parts of the robot are with respect to one another: ROS does all that for you.

The greatest virtue of ROS, which is free and open source, is that it can run not only on PR2 but also on pretty much any other robot with a computer. Indeed, the ROS community has grown to thousands of developers, and ROS is now running in everything from small humanoids to big industrial robots. ROS, now maintained by the Open Source Robotics Foundation, is bringing us closer to a world where people don't have to re-create basic software modules every time they build a new robot.

If all goes well, ROS or software like it will allow developers to focus on high-level applications rather than basic systems operations as they build ever more sophisticated capabilities into their robots. Those developers will then package their creations into apps, which users will download from robot app stores. Perhaps robots will make these purchases themselves. Or maybe newly created functionalities will be stored in a cloud-based knowledge repository, which robots would access to learn new skills. At the same time, robots would contribute to this repository on their own: If a robot learned to grasp a certain teacup, it would upload information describing how to do that in a way other robots would understand. That is, tomorrow's robots would learn not just from people but also from one another.

And if we glimpse perhaps a few decades ahead, we see robots becoming more than just labor savers in our homes. As they become more common–and as we become more accepting of them–certain models will also serve as companions to many of us. You may find this idea uncomfortable, even repulsive. But the next generations, growing up alongside robots, will embrace them–or at least demand that they have more "personality" than a disk-shaped vacuum bot.

Already filmmakers are beginning to speculate about our relationship with machines in the near future. In *Robot & Frank* (2012), a grumpy retiree is initially reluctant to accept the robot servant his son buys him, but he soon finds its presence indispensable. In *Her* (2013), a lonely writer played by Joaquin Phoenix becomes romantically attached to a talking operating system. "Like when I talk to her," he says, referring to the OS, "I feel like she's with me."

Ken Goldberg, a roboticist at UC Berkeley, doesn't believe that ever smarter machines will replace human contact. "But people aren't always available," he says. "So having a robot to tell me jokes, play videos and pictures of my past, and keep me company, I think that's something we're going to see."

To be sure, nobody knows whether robotics will evolve exactly this way. But we think it *should*. Roboticists will have to overcome many obstacles to get there, but a future in which robots become true helpers and at least surrogate friends is awfully appealing. Of course, they'll fold our towels too. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/robots0614

FICTION

THE FUTURE WE DESERVE

SOMEONE TO WATCH OVER ME

Every technology has unintended consequences

By **Nancy Kress**

"I STILL HATE THIS," TREVOR SAID. "THAT YOU'RE DOING this to Becky." • "So you've told me," I said wearily. "Many times." • We sat in the clinic waiting room, done in Martian rust reds, very trendy for such an illegal operation. But, then, this was very upscale illegality. Trevor, who had so much money he never thought about it, hadn't asked how I was paying for Becky's surgery, and I hadn't volunteered that I'd cashed in my retirement fund at Payne, Jeffers. We'd been waiting on the rust-red conformachairs, which were not as comfortable as advertised, for nearly an hour. • Trevor scowled at me. "Amanda, as a tactic this lacks–" • "Sweetness," I said. "I know. I'm not a sweet person, Trevor. This is a surprise? You've known this about me since we were nine. We didn't become friends because you value sweetness." • "I didn't–"

ILLUSTRATION BY Martin Ansin

But I was, all at once, beyond restraint. I turned on him. "And Jake didn't marry me for sweetness, either. Who wants to go to bed with a lump of marzipan–he used to say that to me! And he didn't leave me for lack of sweetness, either, or he wouldn't have chosen...what does *she* have that I don't?"

My voice had risen to a shout. The three other people in the waiting room, two of whom were holo-masked, stared. I twisted my hands together and spoke more softly. "He's just erased me from his life. That's what I really can't stand–that he acts like I never existed at all."

Trevor put his arms around me. I collapsed against his thin chest and narrow shoulders–delicate frames were hot just now with gays–and sobbed quietly. The man sitting two chairs away moved to four chairs away.

After I finally blew my nose, I said, "Trevvy, I have to know. Jake was the love of my life."

"Jake is a cheating and lying bastard, and anyway, I'm the love of your life."

"Not carnally."

"Overrated."

"You don't believe that."

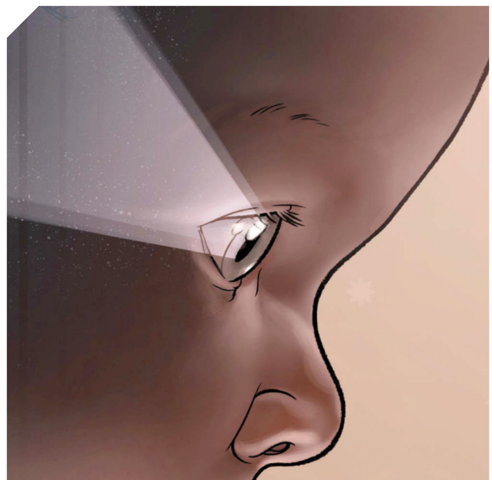
"Well, no." He held me at arm's length. "You look like a dead spot in the ocean. Go put on some makeup. Obsession is not a good look for you. Anyway, Becky should be the love of your life."

His expression stopped my remaining sniffles. Trevor always smiles and he is never, ever critical of me. Not seriously. I said, "She is."

He didn't bother to correct the lie. But he looked away from me, and something in my neck went cold. I'd lost my soon-to-be-ex husband. If I lost Trevor, too....

"I'm here, Amanda. Always. And no, I don't need sweetness from you. I just need–"

My wristband brightened and said, "Ms. Rydder, the surgery went fine, and you can see Rebecca now. First door to your left."



"I ran the camera images of Jake as Becky saw him until I found a good one"

I charged through the door. Becky lay in a smartcrib, watching a holo-mobile two feet above her. Bright, nonexistent shapes twisted and flowed in the air. Becky's plump little hands reached for them until she saw me. She crowed with delight, and I picked her up and cuddled her, studying her right eye.

It was clear, stained-glass green with thick, dark lashes. Just like Jake's eyes.

No scars on the smooth baby skin.

No grogginess from the anesthesia, no pain, no cloudiness in her iris.

You couldn't tell that anything had been done to her at all.

USING THE SOFTWARE was as uncomplicated as the implant itself. What was hard was setting it up. The manufacturer doesn't do that for you, understanding more than anyone the absolute necessity of customized, unhackable encryption on dedicated and shielded computers. Most wearers of Opti-Cam implants are not six-month-old infants. Last month alone, six major mobsters were indicted and an Asian dictator assassinated using information from Opti-Cams.

Trevor set up my system. It was pretty minimal: receiver, screen, retransmitter, basic encryption. He protested the retransmitter. "This data isn't something you should view on anything but this one screen here in your bedroom, off-line for all the Internets. Don't retransmit to your wrister or, *quod di prohibeant*, to any screen anywhere at your job. Do I have to remind you that this whole setup is illegal?"

"Just get it working. And drop the Latin–it's pretentious."

"You never did have any sense of verbal fashion, Mandy. No, don't touch that... wait a minute...there."

The screen brightened to an expanse of white. I was about to protest that the system didn't work when I realized: Becky was staring at the ceiling.

She lay in her crib across the room, drowsy and blinking. The white expanse disappeared, reappeared, disappeared again. I said, too shrilly, "Mobile on," and her smartcrib activated it. Becky's eyes opened wide and she cooed. My screen showed somersaulting kittens made of light, seen from Becky's perspective as the camera behind her cornea sent its images to the receiver.

"Mobile off." The kittens disappeared. I crossed the room and loomed over Becky, looking back over my shoulder. On-screen was her view of me, head turned away.

Trevor said, "I still don't think you've thought this through. And I still hate it. Becky–"

"Won't know a thing. She doesn't feel the implant, and the images don't get stored in her brain, at least not any more than they would from her own vision. Nothing connects to her memory. There are dozens of studies proving that."

"With adult subjects. Not infants."

"Infants remember even less than we do."

"I wish you remembered less," Trevor said. "Remembered less, felt less, schemed less–"

I'd stopped listening to him. I watched Becky watch me until her lids fell into sleep and the screen went blank.

This was Wednesday. On Friday Jake would pick up Becky for his weekend of shared custody.

"WHAT'S WITH YOU?" FELICITY SAID to me in the ladies' room nearest our cubicles. "You're jumpy as a cat."

"Cats aren't particularly jumpy. Neither am I. Just stressed about the GloBiz account."

Felicity frowned, but before she could point out that GloBiz was consistently thrilled with our campaign for them, I was out of the ladies' room, out of the building, in a cab home. Only 4:00 p.m., but so what? Even a copywriter deserves a dangerous, illegal, utterly stupid hobby.

In my bedroom I turned on the dedicated computer. Becky gazed at the back of a head in a moving car. One head, not two. Jake, alone, had picked her up at day care.

Then his apartment, not Pam's. I had never been inside either one, but I recognized his half of what had once been our furniture. He put Becky on the floor to crawl, and whenever she glanced over at him, I glimpsed the slippers I'd given him for his last birthday.

In college, I'd been a film major. No Fellini retrospective, no Welles film work, had ever enthralled me like the images on my screen that Friday evening. Jake's slippers, Becky's toys, a rubber ducky floating in the bathtub. Quick shots of Jake's face, laughing or talking to her–why didn't the implant have audio! Pam did not appear. When Becky finally fell asleep, I turned off the computer and then sat for a long time in the dark, tears running down my face, rage in my heart.

He had no right to do this to me. To Becky. To live his life as if I'd never occupied the center of it.

At midnight I gave in and keyed his number into my cell. He answered sleepily. "Hello?"

Not breathing, I clutched the phone.

More sharply: "Hello?" And then, "Amanda, if this is you, you're violating the restraining order. Please stop. I mean it this time. I'll go back to court if I have to."

I said nothing. Tears and rage, tears and rage. Long after he hung up, I clutched the phone as if I could crush it.

ON SATURDAY, PAM APPEARED IN Becky's field of vision.

At first I got only flashes of her; Becky was not interested in focusing on this unknown person. It was eerie to glimpse a red-shirted elbow, the toe of a black boot, the back of a blond head. It disassembled her, made her less than real. Eventually, however, she sat down in front of Becky and fed the baby strained applesauce.

Instantly, I wanted to leap through the lens and shove her away from my baby. Leave her alone, you bitch, she's *mine*! Pam was pretty but not gorgeous, a girl-next-door type if the door happened to open on a Hamptons beach house. Sun-streaked hair, fine sun lines around brown eyes, no makeup, vintage Lululemon workout clothes. On the street I'd never have noticed her. Her body looked nicely curved but neither buxom nor model-elegant. What did she have that I didn't?

Becky spat applesauce at her and the view vibrated–she must have been giggling. Pam giggled back.

Stop. Leave her alone! She's mine!

He's mine.

BY SUNDAY AFTERNOON, WHEN JAKE brought Becky back, I had slept a total of three hours. All weekend I'd sat by the screen, seldom eating, scarcely going to the bathroom. Becky might wake in the night; there might be something to see. It was, as I'd discovered online, a one-bedroom apartment. Did Jake wheel her crib out into the living room so he and Pam could have sex in the bedroom? Or did they do it with Becky asleep beside them?

By order of the court, ever since that stupid misunderstanding two months ago, Jake and I had no contact when Becky was returned on Sunday. Jake brought his sister with him every single week. Linda brought Becky into my building, and the two of us did not exchange a word.

I unwrapped Becky and studied every inch of her, looking for–what? Anything amiss, a bruise or a dirty diaper or ripped pj's. There was nothing, of course. Jake had always been a terrific father.

The baby was asleep by seven o'clock. I called Trevor to come over; my call went straight to voice mail. Felicity had a date. TV was boring. I roamed the house, unable to sit for even a moment.

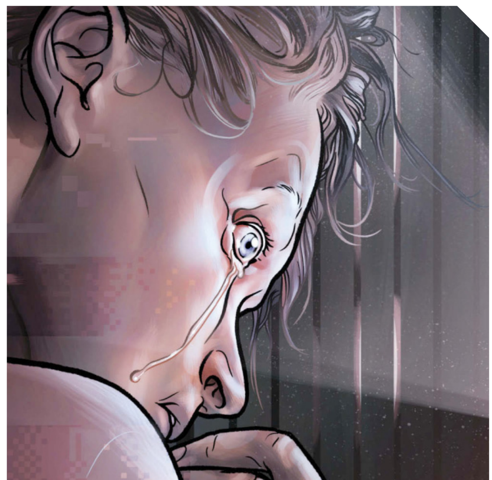
Until I stopped cold, feeling my own mouth open into an O. After checking on Becky one last time, I brought the small, dedicated computer into the living room and connected it to my wall system.

TREVOR HAD MADE HIS FORTUNE with Holo-Shop. He invented it, patented it, and sold it for an exorbitant sum plus royalties to Microsoft.

There had been other holographic conversion programs on the market, but they were quirky, experimental, difficult to use. Holo-Shop was none of those, and the results were sharper than anything before it. You brought up a flat image on a screen, set the parameters you wanted, and touched the H-S icon. The image sprang from the screen in holographic three dimensions. It could be small or large, although the larger you made it, and the farther away the hologram from the screen, the lower the resolution. A three-inch rose was a miracle of dense perfection; a room-sized puppy was insubstantial vapor.

Holo-Shop could not evoke moving images, not yet, although Microsoft was reportedly working on it. Meanwhile, advertisers and artists and retail outlets manipulated holograms to sometimes powerful effect, sometimes laughable kitsch. Ditto the millions of users who wanted the pyramids to decorate their trendy Egyptian-themed living room but to disappear when they needed to set up a card table for poker.

I ran the camera images of Jake as Becky saw him until I found a good one: Jake crouching on the floor, smiling, green eyes alight, arms extended for the baby to crawl into them. I froze the image, projected it with H-S, and fooled with it for a while. When it was done, Jake sat life-size on my bedroom floor, ghostly enough to see the dresser behind him, arms outstretched. The dresser didn't matter. I got down on the floor and moved to sit in the circle of his arms.



"I am not sane, I thought, which was my last sane thought"

THE SECOND WEEKEND THAT JAKE had Becky, Pam was there all weekend. I watched them every minute that Becky was awake. They kissed in the kitchen, took Becky to the park, watched something on TV while she crawled around the floor. Pam wore Carson Davies boots in calfskin, $800. When Trevor called with tickets to the hottest play in town, I told him I had the flu. By Sunday afternoon, when Linda handed Becky back to me, I was groggy from sleeplessness, reeking from not bathing. I didn't look at Linda looking at me.

I once saw a show about toxoplasmosis, a parasitic disease. When mice contract it, they lose their natural fear of cats, making it easier for cats to eat them and the parasite to get into the cat. There was some evidence from brain scans that the mice realized this lack of fear was stupid, but they couldn't help themselves. They were compelled to let the cats see them.

At work I accomplished nothing. I'd set the retransmitter to send the images of Jake and Pam to my wrister; the hell with what Trevor said. Whenever I could, I ducked into the ladies' room and brought up images to study. Felicity went from warmly supportive ("You don't feel well? Oh, I can finish that copy, Amanda") to faintly resentful ("You haven't even started on the McMahon account stuff? But we got it over a week ago").

On Thursday night, Trevor called. I told him I had the flu. On Friday night, he let himself into my apartment with his emergency key. I barely had time to dart out of the bedroom and close the door.

"Trevor! I told you I'm sick!"

"It's not flu season, Mandy." His handsome face looked strange without its habitual smile.

"If I say I have the flu, then I have the flu!"

"I don't think you do. You're doing it again, aren't you? Two restraining orders and a court fine weren't enough?"

"I'm not. I'm not stalking Jake."

"Swear on pussy willows' pussies?" Our childhood oath; at ten years old it had seemed hilarious.

"Swear on pussy willows' pussies."

"Then you're obsessing over the Opti-Cam images."

"Isn't that my business?"

Trevor lost his temper, something even rarer than losing his smile. "Oh, Christ, Mandy, you're my business! Don't you know that if I were straight, you and I would have married and had three Beckys of our own? Don't you know how much better I'd have been for you than Jake? I can handle your intensity, he couldn't. And I know when you're lying to me."

"Please go, Trevor. I'm not up to this right now, really I'm not–"

He left, slamming the door behind him. Once, nothing in the world would have kept me from following him. Trevor, my best friend, my support and confidant....

On the screen in the bedroom, Becky lay in her infant seat, studying her bare toes. She must have just woken up. On the rug, barely within the circle of her unknowing vision, Jake and Pam made love.

Frantically I keyed in his cell number. Anything to disrupt them, anything! The call went to voice mail. "Stop!" I screamed. "Stop, stop, stop!" The cell must have been on silent; they didn't stop.

I am not sane, I thought, which was my last sane thought.

I CALLED IN SICK TO WORK ON MONday, Tuesday, Wednesday. I never left my bedroom. It began to smell: of Becky's diapers, piled in the corner whenever I changed her. Of a pizza molding on the dresser. Of me.

On Thursday morning, Trevor returned.

"Mandy?"

"Go away! Go away!" I'd waited all week for 10:00 a.m. on Thursday! Trevor was not going to spoil this!

"Mandy...oh my God." He stood in the door to my bedroom. Becky gurgled in her swing. She was dressed in her snowsuit; the window stood open to help with the stench.

"Go away!" I barely glanced at him–it was 9:57!

"Mandy, darling, whatever you're going to do...don't."

9:58.

"Let me help you. You know we've always helped each other."

"Don't touch me!"

"I won't. You know I won't if you don't want me to. I'm just going to pick up Becky, okay? Here we go, sweetheart, come to Uncle Trevor...."

9:59.

Jake's law office was superefficient. The partners would be gathering in his spacious office for the regular Thursday morning meeting. His wall screen would be on, ready to bring up the week's data. He didn't know I had his office password; I'd stolen it right after he told me he was leaving me, but despite everything that had led to the restraining order I'd never used it. Until now.

Trevor said, "Mandy, what are you doing? Put down your cell if you're calling the cops. I'm not here to force you to do anything you don't want to do, I promise. Put down the cell."

10:00.

I pushed both buttons simultaneously, my cell and the "Send" button on the computer. The phone number bypassed Jake's office answering system–a direct line for privileged clients who needed to reach their lawyer instantly for some legal emergency. Jake would not recognize the number of my new, throwaway cell. His voice said, "Hello?"

Now it would happen. Now I would get what I had been trying for so long, what I needed more than food or water or even Becky: I would get a reaction from Jake. The image of him and Pam naked on the rug would burst from the wall screen in his office in all its color-saturated, three-dimensional luridness, and Jake would know I had done it. That he could not erase me.

"Hello? Who is this?" Jake said, still calm. "Can I help you?"

I waited.

Nothing happened.

No one in the background gasped or laughed or said, "What the hell–?" Nothing.

Jake tried one last "Can I help you?" and then cut the connection.

Trevor, patting Becky's back, said softly, "Mandy...."

I cried, "Why didn't it work?"

Trevor's face changed. His gaze moved to the computer. He knew, then; he was always smarter than anybody else I knew. He said, "Because Jake knew you'd do something like that. He put a detailed blocker on his system."

"I just wanted him to acknowledge I exist!"

"Oh, he acknowledges it," Trevor said. "How do you think he knew what you'd do?"

He held Becky, now squirming in her snowsuit, away from him and stared into her eyes, first the right and then the left, again the right, again the left. "The technology's available to everyone. Including Jake."

I DON'T LIKE TO LIE TO TREVOR. Sometimes, however, you have to do certain things you might not want to do. He went with me to the clinic, but of course he couldn't sign any papers; he is not related to Becky. I told him I'd had both Opti-Cams removed. I swore on pussy willows.

Now I stand in my bedroom, which sparkles with cleanliness. Becky sits in her swing, gurgling at me. I lean closer to her. My hair, clean and shining, swings toward her. My makeup has been professionally done. My cleavage gets help from a $200 bra. I smile at my baby.

Jake is watching. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/kress0614. This is one of six hard science fiction tales that will appear in *Coming Soon Enough*, a forthcoming e-book from *IEEE Spectrum*, featuring work by Greg Egan, Brenda Cooper, and others.

CONTINUED FROM PAGE 31 | mining outfits—but for water. The firm expects to extract it from some kinds of asteroids simply by using heat from concentrated sunlight, says Chris Lewicki, the company's president and chief engineer. "Our focus isn't necessarily on inventing new technology," he says. "It's on doing with a small team what once used to take the government."

GATHERING RAW MATERIALS IS ONLY THE BEGINNING. TO build up infrastructure, we must also develop ways to fabricate and manipulate structures in space.

The U.S. Defense Advanced Research Projects Agency has been making headlines with the Phoenix project, which would use advanced robotics and modular components to construct spacecraft in orbit. Among other uses, this combination could extract the antenna from a defunct satellite and build a new one around it.

A company called Tethers Unlimited, based in Bothell, Wash., hopes to fabricate structures from scratch, on even larger scales. Its project, called SpiderFab, aims to use robotic arms to build up and maneuver across 3-D-printed structures while floating free in orbit. The goal is to create objects that are too big to be folded into the top of a rocket. "What we're trying to do is figure out how to make it not ridiculous to talk about antennas that are hundreds or thousands of meters in diameter," says CEO Robert Hoyt. One of the biggest challenges Tethers is tackling now is how best to manage the thermal environment, Hoyt says. The temperature can vary by hundreds of degrees in orbit, and large temperature gradients could prevent structures from properly cooling and hardening, causing wild deformations.

The first 3-D printer to go into space won't suffer such problems. Built by Made in Space, a start-up based in Moffett Field, Calif., and set to be delivered to the International Space Station later this year, it will be safely ensconced in a climate-controlled glove box. The printer makes objects out of heated polymer filament, just as many terrestrial 3-D printers do, but it has been altered to work in microgravity. The team logged hundreds of hours on parabolic flights to perfect the technology, says lead engineer Michael Snyder, but he won't disclose what sets it apart from typical 3-D printers. "That's our special sauce," he says. The company plans to send an improved version of the printer to the station in 2015 and rent time on it to anyone who might want to print in space.

Both SpiderFab and Made in Space printers would require carrying material up from Earth to be used as the raw material for construction. Printing structures using material gathered elsewhere is still on the horizon. Although the European Space Agency, NASA, and others have looked into building very crude structures—mostly human habitats and landing pads—out of lunar soil, at present there are no plans to try out these ideas in space.

Still, many say the basic ingredients needed to build a true space infrastructure are more or less ready. Now we must find a way to combine them. Only then will our machines be able to prepare the way for our own forays to the moon, the planets, and the stars, turning us at last into a truly spacefaring species. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/space0614


Advance Your Career
With the Experts at Wiley-IEEE Press
Stuff You Don't Learn in Engineering School
Skills for Success in the Real World
CARL SELINGER
ISBN: 978-0-471-65576-3
Fast-Tracking Your Career
Soft Skills for Engineering and IT Professionals
Wushow "Bill" Chou
IEEE
IEEE PRESS
WILEY
ISBN: 978-1-118-52178-6
Ten Essential Skills for Electrical Engineers
BARRY L. DORR
IEEE
WILEY
ISBN: 978-1-118-52742-9
Negotiating Cultural Encounters
Narrating Intercultural Engineering and Technical Communication
EDITED BY Han Yu · Gerald Savage
WILEY
IEEE
ISBN: 978-1-118-06161-9
Information Overload
An International Challenge for Professional Engineers and Technical Communicators
EDITED BY Judith B. Strother · Jan M. Ulijn · Zohra Fazal
WILEY
IEEE
ISBN: 978-1-118-23013-8
Slide Rules
Design, Build, and Archive Presentations in the Engineering and Technical Fields
Traci Nathans-Kelly · Christine G. Nicometo
IEEE
WILEY
ISBN: 978-1-118-00296-4
ENGINEERING Your RETIREMENT
Retirement Planning for Technology Professionals
MIKE GOLIO
ISBN: 978-0-471-77616-1
ARE YOU AN EXPERT IN YOUR FIELD?
TO LEARN MORE ABOUT PUBLISHING WITH WILEY-IEEE VISIT:
HTTP://WWW.IEEE.ORG/PUBLICATIONS_STANDARDS/PUBLICATIONS/PRESS/AUTHORS/BOOKS.HTML
IEEE
VISIT: WWW.WILEY/IEEE.COM
WILEY

CONTINUED FROM PAGE 55 | accidents will be rare enough to be as shocking as they should be.

ASIMOV WROTE NOT OF ROBOCARS BUT OF THEIR consequences. He thus followed the sci-fi rule of his colleague, Frederik Pohl, "to predict not the automobile but the traffic jam."

In that spirit, let's assume that fully autonomous vehicles mature without worrying too much about the technology needed. What would happen? Briefly, our roads, our towns, and the frames of our lives will change, as they did when cars were first introduced.

"Approximately every two generations, we rebuild the transportation infrastructure in our cities in ways that shape the vitality of neighborhoods; the settlement patterns in our cities and countryside; and our economy, society, and culture," writes Marlon G. Boarnet, a specialist in transportation and urban growth at the University of Southern California.

Robocars would be shared, and that would make them both convenient and cheap to use. Vehicles would be fewer in number but far more heavily used, picking up new passengers near where they left the last ones off. Such vehicle-sharing schemes are spreading, even though today's dumb vehicles tend not to be there for you when you need them. One reason is that they accumulate at popular destinations. It'd be different for a car that could come when you called and leave when you were done with it.

"Certainly, car sharing is an option," says Ralf Herrtwich, a leader in Mercedes's autonomous car project, in Stuttgart. "Get the vehicle at your command, drop it at your convenience, no parking."

Brave talk, but Mercedes owners must quail at the thought of a commodified sharemobile. Who would pay a higher fare for a robotaxi lined in burled walnut, with leather seats and a perfume dispenser—features actually offered in the 2014 Mercedes S-Class?

There's one bunch who won't be able to pay for such fripperies: professional drivers. Say good-bye to all of them—5 million people in the United States alone. In a world of autonomous cargo carriage, machines could hitch trucks to standardized containers of stuff. Then, at distribution points, other machines could transfer their contents to smaller trucks—or perhaps to robots so small they could safely roll along sidewalks. Picture a little triwheeler that would fail only by stopping, not by falling on your head, as one of Amazon.com's proposed quadcopter delivery drones might do.

"Could we enter into a world where things are brought to us in a Segway-size pod?" wonders Burns of Columbia. "And if so, what does that do to retail big-box stores?"

Say bye-bye as well to the soccer mom. Parents will call a robocab, set its parental controls, lock the car doors, and send their teenage daughters to practice or maybe to the library, making it impossible for them to cruise "through the hamburger stand now," as the Beach Boys sang in 1964.

The self-driving car will free us of much drudgery, true, but future generations may never know the freedom of the open road. And though the work such a car will do will be of great value, it probably won't inspire many songs. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/cars0614

Spotlight on CLEAN TECHNOLOGY

"In Denmark you can find great engineering jobs and develop yourself professionally. Especially in the wind sector you can learn from the best people in the industry and advance your career in a stable job market."

Mireia Marrè,
Advanced Engineer from Spain.
Working in the wind industry
in Denmark since 2010.

DENMARK IS HIRING

Are you looking to further your cleantech career in an innovative environment with excellent work/life balance? Think Denmark!

Visit **cleantech.talentattractiondenmark.com**

IEEE Open Access

Unrestricted access to today's groundbreaking research

- Hybrid journals known for their established impact factors
- New fully open access journals in many technical areas
- A multidisciplinary open access mega journal spanning all IEEE fields of interest

Learn more about IEEE Open Access
www.ieee.org/open-access

IEEE

ShanghaiTech University Faculty Search

The newly launched ShanghaiTech University invites highly qualified candidates to fill multiple tenure-track/tenured faculty positions as its core team in the School of Information Science and Technology (SIST). Candidates should have exceptional academic records or demonstrate strong potential in cutting-edge research areas of information science and technology. They must be fluent in English. Overseas academic connection or background is highly desired. ShanghaiTech is built as a world-class research university for training future generations of scientists, entrepreneurs, and technological leaders. Located in Zhangjiang High-Tech Park in the cosmopolitan Shanghai, ShanghaiTech is ready to trail-blaze a new education system in China. Besides establishing and maintaining a world-class research profile, faculty candidates are also expected to contribute substantially to graduate and undergraduate education within the school.

Academic Disciplines:
We seek candidates in all cutting edge areas of information science and technology. Our recruitment focus includes, but is not limited to: computer architecture and technologies, nano-scale electronics, high speed and RF circuits, intelligent and integrated signal processing systems, computational foundations, big data, data mining, visualization, computer vision, bio-computing, smart energy/power devices and systems, next-generation networking, as well as inter-disciplinary areas involving information science and technology.

Compensation and Benefits:
Salary and startup funds are highly competitive, commensurate with experience and academic accomplishment. We also offer a comprehensive benefit package to employees and eligible dependents, including housing benefits. All regular ShanghaiTech faculty members will be within its new tenure-track system commensurate with international practice for performance evaluation and promotion.

Qualifications:
- A detailed research plan and demonstrated record/potentials;
- Ph.D. (Electrical Engineering, Computer Engineering, Computer Science, or related field);
- A minimum relevant research experience of 4 years.

Applications:
Submit (in English, PDF version) a cover letter, a 2-page research plan, a CV plus copies of 3 most significant publications, and names of three referees to: sist@shanghaitech.edu.cn by June 30th, 2014 (until positions are filled). For more information, visit **http://www.shanghaitech.edu.cn.**

Director

Advanced Radar Research Center

The University of Oklahoma seeks an exceptional, dynamic leader to serve as Director of its Advanced Radar Research Center (ARRC).

The ARRC builds upon a university, government and industry alliance that leads the world in the development, testing, operational deployment, and support of advanced weather radar systems. Through a recent strategic initiative, the ARRC has expanded capabilities in radar and other electromagnetic technologies, with applications in surface, airborne and space-based defense, security and intelligence. Principal capabilities of the ARRC include design/prototyping of both large and small, fixed and mobile radar systems; phased array technology; digital signal/array processing; automated algorithms; decision support tools; data assimilation; and end-user training. Multi-functional, dynamically adaptive radars are now being evaluated in the field and more than two-dozen radars are located across Oklahoma, including both operational and research systems for weather, air surveillance, and security applications. The ARRC currently consists of 16 faculty members, 16 post-doctoral scientists, 7 staff members, and over 60 graduate students, across the disciplines of engineering and meteorology.

In support of our highly regarded programs in radar remote sensing and related fields, the University of Oklahoma opened its state-of-the-art Radar Innovations Laboratory (RIL) in March 2014. Located adjacent to the National Weather Center on the OU Research Campus, the RIL will be the new hub of ARRC operations. The 36,000-square-foot, $15 million RIL will provide world-class facilities to move ideas for next-generation radar, microwave electronics and related technologies from conception through research, development and full prototyping. The facility features a full suite of microwave measurement equipment and two anechoic chambers enabling far-field, near-field, and radar cross-section measurements, down to 300 MHz. The lab will serve both the research and educational missions of the University by providing a hands-on, active learning environment for OU students.

The Association of University Research Parks named OU's Research Campus the 2013 Outstanding Research Park http://vpr-norman.ou.edu/). The Research Campus hosts the National Weather Center (NWC), one of the largest facilities of its kind in the world, housing twelve University of Oklahoma, state, and federal organizations with more than 650 faculty, researchers, support staff, and students. The NWC includes NOAA's National Weather Service Forecast Office, Storm Prediction Center, National Severe Storms Laboratory, Radar Operations Center, OU-NOAA Cooperative Institute for Mesoscale Meteorological Studies, and School of Meteorology. The School of Electrical and Computer Engineering is housed nearby in the new Devon Energy Hall.

The ARRC Director provides intellectual leadership in a multidisciplinary environment. The Director works in collaboration with private industry and federal agencies and carries out a vigorous program of teaching, research, and service that attracts exceptional students and prepares them to become future leaders in the development and application of advanced radar technologies. The ARRC Director reports to the Executive Board, consisting of the Dean of the College of Engineering, the Dean of the College of Atmospheric and Geographic Sciences, and the Vice President for Research. The successful applicant must be an internationally recognized scholar with a science or engineering doctoral degree and an outstanding record of professional achievement, commensurate with appointment to a tenured position at the Associate or Full Professor level within the School of Meteorology (College of Atmospheric and Geographic Sciences) or the School of Electrical and Computer Engineering (College of Engineering). Demonstrated ability of working collaboratively with private industry and eligibility to obtain a security clearance are highly desired.

To apply, please submit a letter of interest including a statement of research goals and teaching vision, current curriculum vitae, and the names of four or more people who can serve as references (with full mailing and e-mail addresses, telephone, and FAX numbers). Screening of applications will begin on 15 Sept. 2014 and will continue until the position has been filled.

Please address all correspondence to the two Co-Chairs of the Search Committee:

Dean Thomas Landers
AT&T Chair
College of Engineering
University of Oklahoma
202 W. Boyd Street CEC 107
Norman, OK 73019
PH: 405-325-2621
FAX: 325-7508
E-mail: landers@ou.edu

Dean Berrien Moore
Vice President for Weather and Climate
College of Atmospheric and Geographic Sciences
University of Oklahoma
120 David L. Boren Blvd.
Norman, OK 73072
PH: 405-325-3095
FAX: 405-325-1180
E-mail: berrien@ou.edu

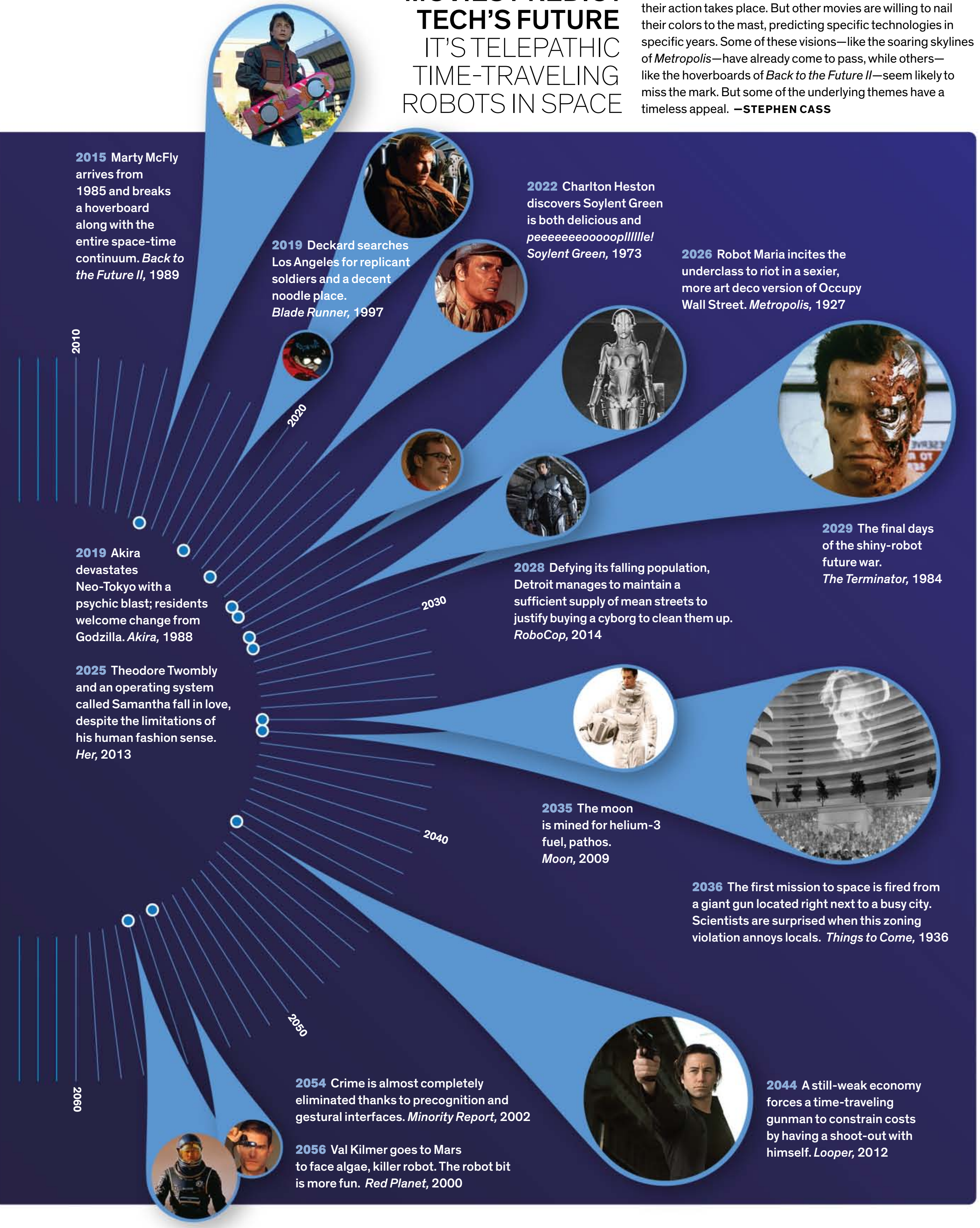
The University of Oklahoma is an Affirmative Action, Equal Opportunity Employer.

Women and minorities are encouraged to apply.

Protected veterans and individuals with disabilities are encouraged to apply.

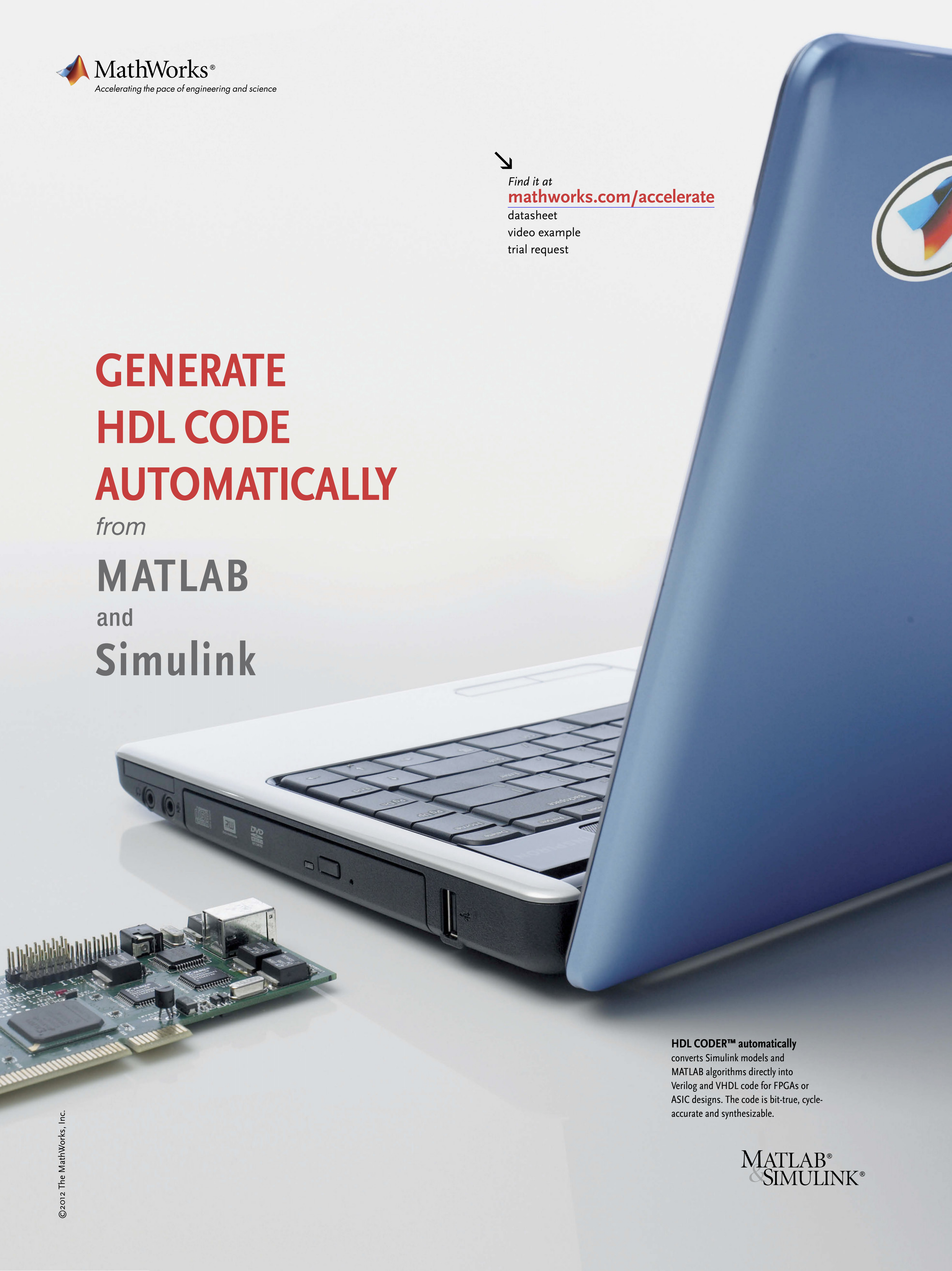
MOVIES PREDICT TECH'S FUTURE
IT'S TELEPATHIC TIME-TRAVELING ROBOTS IN SPACE

Many futuristic movies are vague about the year in which their action takes place. But other movies are willing to nail their colors to the mast, predicting specific technologies in specific years. Some of these visions—like the soaring skylines of *Metropolis*—have already come to pass, while others—like the hoverboards of *Back to the Future II*—seem likely to miss the mark. But some of the underlying themes have a timeless appeal. **—STEPHEN CASS**



2036: GETTY IMAGES; ALL OTHERS: ALAMY

INFOGRAPHIC BY Carl DeTorres


MathWorks®
Accelerating the pace of engineering and science
Find it at
mathworks.com/accelerate
datasheet
video example
trial request
GENERATE
HDL CODE
AUTOMATICALLY
from
MATLAB
and
Simulink
HDL CODER™ automatically converts Simulink models and MATLAB algorithms directly into Verilog and VHDL code for FPGAs or ASIC designs. The code is bit-true, cycle-accurate and synthesizable.
MATLAB® & SIMULINK®
©2012 The MathWorks, Inc.