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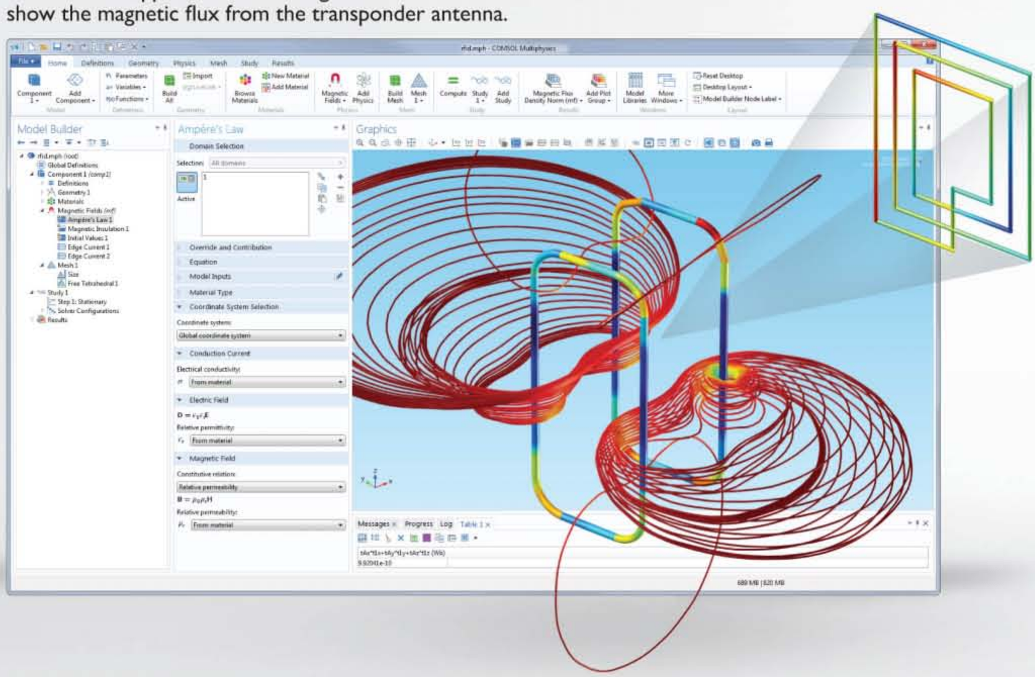

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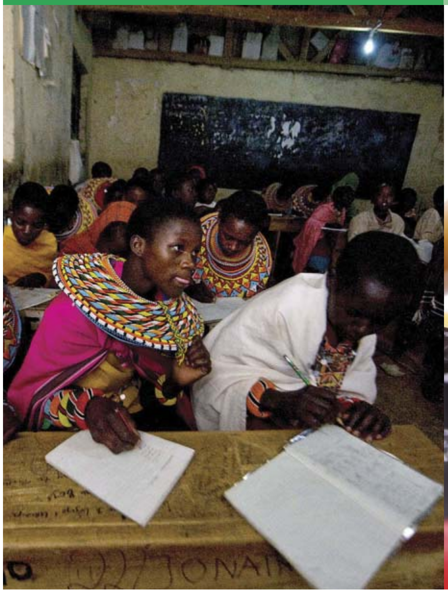
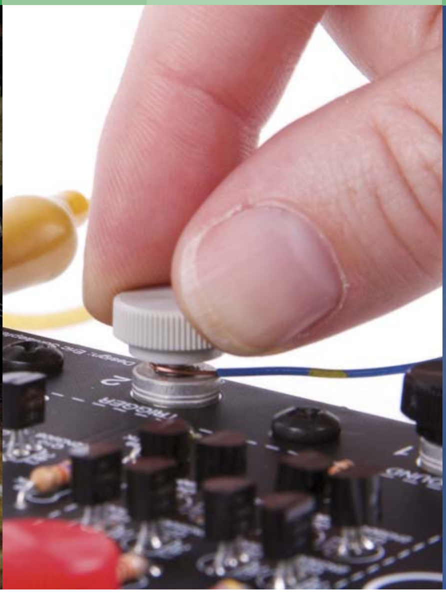


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- **MEET THE 2015 CANDIDATES** Frederick Mintzer and Barry Shoop are the candidates for 2015 IEEE president-elect. The winner will serve as 2016 IEEE president.
- **PART-TIME PASSIONS** One member builds regenerative radios, while another writes essays and poetry.

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BACK STORY_

In the Hot Zone

REPORTING IN A NUCLEAR fallout zone is not easy, as Associate Editor Eliza Strickland discovered during a trip to Japan's Fukushima Prefecture. Strickland [at left] visited the region's evacuated ghost towns while on assignment for "Fukushima's Next 40 Years," in this issue. The article describes the monumental task of decommissioning the ruined Fukushima Daiichi nuclear power plant, which experienced meltdowns in three of its six reactors after a tsunami in March 2011.

The town of Okuma, just a few kilometers from the blasted reactors, is far too radioactive for its former inhabitants to return. In one hot spot, a year-round resident would receive three times the dose considered acceptable for a Fukushima Daiichi cleanup worker. Nevertheless, two town officials agreed to take Strickland on a tour. In the photo, the group is seen talking outside a nursing home that was hastily evacuated during the nuclear emergency.

Even if the power plant is successfully dismantled, the fate of towns like Okuma is uncertain. Okuma was a prosperous village of 11 500 people before the accident. For its residents to come back, all of the town's houses, roads, fields, and woodlands would have to be decontaminated, at a cost that is now largely incalculable. In the most recent survey of displaced Okuma residents, only 11 percent expressed a strong desire to return to their homes.

During her tour, Strickland was deeply saddened by the sight of abandoned houses and overgrown rice fields. "The town's mayor told me his family had lived there for 19 generations," she recalls. "He had such pride in Okuma." ■

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ADMINISTRATIVE ASSISTANTS
Ramona Foster, r.foster@ieee.org
Nancy T. Hantman, n.hantman@ieee.org

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Evan Ackerman, Mark Anderson, John Blau, Robert N. Charette, Steven Cherry, Peter Fairley, Mark Harris, David Kushner, Robert W. Lucky, Paul McFedries, Prachi Patel, Richard Stevenson, Lawrence Ulrich, Paul Wallich

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PHOTOGRAPH BY **Hiroko Aihara**

CONTRIBUTORS_

Bill Beck

Beck, who wrote "Lasers Light Up the Silver Screen" [p. 24], is president of BTM Consulting and cofounder and former chairman of LIPA, the Laser Illuminated Projector Association, which promotes the adoption of laser-illuminated digital cinema projectors. In a long career as a contrarian entrepreneur, he started four businesses involving unlikely applications of fiber optics and lasers. He holds a BA degree from Dartmouth College, where he dabbled in film criticism, and an MBA from Rensselaer Polytechnic Institute.

Charles Q. Choi

Brooklyn-based writer Choi has reported on both the space around our planet and on geoengineering—schemes that would purposefully alter our climate. But the notion of seizing control of the energy enveloping the planet, which he explores in "Can We Hack the Van Allen Belts?" [p. 11], was a new one to Choi. "The idea that one could engineer space on such a vast scale amazed me," he says.

Andy Maltz

Maltz, managing director of the Science and Technology Council of the Academy of Motion Picture Arts and Sciences, in Beverly Hills, Calif., writes in this issue about the tough technical challenge of preserving digital cinema for future generations [p. 32]. "It seems only fitting that as a technologist who has contributed to the transition from film to digital moviemaking, I now work on some of the problems that I helped create," he says.

Chris Mueller

While driving through Tijuana, Mexico, Mueller jumps out to snap some sculpted shrubbery for his blog. His camera? A phone. Nevertheless, he's every inch a professional photographer, and he's got more cameras, lights, and batteries than even he can lift in one go. But he matches the tool to the task. He needed all his stuff to photograph quadcopters in three cities in two countries, indoors and out for "Open-Source Drones for Fun and Profit" [p.46].

James Provost

"As a kid I liked taking things apart and seeing how they worked," says Provost, who now specializes in technical illustrations that help explain complex systems. For "Fukushima's Next 40 Years" [p. 38], his artwork details the five steps required to decommission the disaster site in Japan. In "Lasers Light Up the Silver Screen" [p. 24], he depicts the components of tomorrow's movie theaters. Tackling multiple assignments for one issue wasn't a problem. "I don't mind tight deadlines," he says.

PHOTO-ILLUSTRATIONS BY **Gluekit**

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SPECTRAL LINES_

AFTER THE ACCIDENT at the Three Mile Island nuclear plant in Pennsylvania, a police officer and security guards stand outside the facility's front gate.

PAUL VATHIS/AP PHOTO

From Three Mile Island to Fukushima Daiichi

IEEE Spectrum's coverage of nuclear disasters, old and new

Editor's note: In this 50th anniversary year of IEEE Spectrum*, we are using each month's Spectral Lines column to describe some pivotal moments of the magazine's history. Here we consider* Spectrum*'s coverage of nuclear disasters in two different eras.*

THREE YEARS AGO, a tsunami came crashing down on the Fukushima Daiichi nuclear plant in Japan, leading to the worst nuclear accident since Chernobyl. As Associate Editor Eliza Strickland explains in this issue in "Fukushima's Next 40 Years," that accident still reverberates strongly in Japan, where all of the country's nuclear plants are currently off line.

Strickland's report continues a decades-long history at *Spectrum* of rigorous coverage of nuclear technology. A milestone was our November 1979 issue on the Three Mile Island nuclear accident in the United States. Though Fukushima and Three Mile Island were very different technically, the parallels between them are enlightening.

IEEE SPECTRUM 1964 / 2014

We started covering nuclear power back in July 1964, in our seventh issue, with an encyclopedic 11-page feature titled "Nuclear Power Today and Tomorrow." It predicted that in the United States, "by year 2000, 45 percent of electric power will be nuclear" (the actual percentage turned out to be around 20 percent). The article concluded that "experience to date, and a series of specific tests have shown that nuclear power is inherently safe. That the public be convinced of this is most important because the growth of metropolitan areas will result in a growing need for reactor plants in or near population centers."

Ouch. It turned out that U.S. nuclear power would face considerably greater public-relations challenges. During the early morning hours of 28 March 1979, a cascade of improbable mishaps led to a partial core meltdown in a reactor at the Three Mile Island nuclear plant, in Pennsylvania.

Some of the initial news accounts of the incident were atrocious: hysterical, wildly speculative, and wrong. There were suggestions that the plant was in imminent danger of blowing up like a bomb, prompting tens of thousands of people to panic and flee the area. Part of the problem was that, in the critical first hours, even the operators of the plant didn't have a good grasp of what was happening inside the reactor.

Amid the chaos, Donald Christiansen, then *IEEE Spectrum*'s editor in chief, saw an opportunity. "He immediately felt we had a special obligation to try to determine what had gone wrong," says Ellis Rubinstein, then a 34-year-old staff editor at *Spectrum*.

Christiansen directed Rubinstein to get to the bottom of the mishap, and gave him an unexpected suggestion. "Every journalist is going to go to Three Mile Island," Rubinstein remembers Christiansen telling him. "They'll all be competing with each other, and there will be a lot of noise and confusion."

Christiansen's advice was to skip that media circus and go instead to Babcock & Wilcox, the company that had manufactured the stricken reactor. "Get them to describe, step-by-step, what happened," Christiansen told Rubinstein. "Draw a diagram of what went wrong," he added. "When you can draw that diagram, you'll be able to write the article."

What happened next bespeaks a bygone era in journalism. Babcock & Wilcox not only agreed to cooperate, it gave Rubinstein an office to use at the headquarters of its nuclear division, in Lynchburg, Va. Staff members tutored him on nuclear power technology and gave him regular updates on what they were discovering, through data collection and simulations, about exactly how the mishap unfolded.

It is inconceivable that a company would offer a journalist such access in today's world of litigation and mistrust. For example, shortly after the 2011 accident, Strickland requested interviews with officials at Tokyo Electric Power Co. (TEPCO), the utility that operates Fukushima Daiichi, but she was rebuffed for months. Ultimately, during her first reporting trip, she was granted only a single and largely uninformative one-hour interview.

> TEPCO freely admits that they don't know how to dispose of Fukushima Daiichi's melted reactors

Rubinstein made the most of his time in Lynchburg. Staying in a nearby motel and speaking daily with experts at Babcock & Wilcox, he pieced together an exhaustive account of exactly what went wrong. He checked everything he learned with nuclear experts in government regulatory agencies, other nuclear companies, and academia. "You can't always trust your sources. Even if they mean well," says Rubinstein, who is now president and CEO of the New York Academy of Sciences.

With Rubinstein's own article as its core and with a dozen other articles edited by him, *Spectrum*'s 1979 report was the first journalistic account to give a minute-by-minute description of the accident. It was so thorough that the first official U.S. government report, which was released within a day or two of *Spectrum*'s issue, had no substantial facts or details that were not in *Spectrum*'s coverage.

The Three Mile Island accident was rated a 5 on the seven-level International Nuclear and Radiological Event scale; both Fukushima and Chernobyl were rated 7. Subsequent analysis indicated that the Three Mile Island accident released fewer than 13 million curies, most of it in the form of relatively harmless radioactive noble gases, as well as 13 to 17 curies of radioactive iodine. This paltry amount of released radioactivity could have no measurable impact on the health of the local population, experts said. Not bad, overall, considering that roughly half of a reactor's core had melted down.

Although there were no apparent health effects, there were certainly financial ones. The cleanup at Three Mile Island cost about US $1 billion and took 14 years. The much more complicated Fukushima cleanup will result in costs, including lost economic assets and opportunities, of up to $250 billion, according to a Japanese survey. For comparison, the country of Belarus has estimated that the damages associated with Chernobyl will total $235 billion.

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SPECTRAL LINES_

The Three Mile Island accident also plunged the U.S. nuclear industry into a dormancy from which it began stirring only recently and rather sluggishly. In 2012, for the first time in 35 years, the U.S. Nuclear Regulatory Commission approved a nuclear construction project, at the Southern Company's Vogtle plant in Georgia. The Vogtle project, which is installing two new reactors, is one of three such construction projects in the United States.

Still, don't count on a U.S. renaissance in nuclear power, at least not anytime soon. Thanks to the boom in shale gas, natural-gas-fired electricity is a bargain. And in 2010, the Obama administration abandoned long-stalled efforts to build a permanent nuclear waste repository in the state of Nevada. Thus nearly 60 years after the start of commercial nuclear power, the United States has no clear plan for the long-term disposal of its 65 000 metric tons of spent nuclear fuel, which will continue to be radioactive for thousands of years to come.

But Japan faces even greater challenges, as Strickland reports in this issue. The decommissioning of Fukushima Daiichi's six reactors, including the three that melted down, will take 40 years and cost untold billions of dollars. "TEPCO freely admits that they don't know how to do this," Strickland says. "They have yet to invent the robots and remote systems that will let them take apart these highly radioactive reactors." And then there's the matter of whether Japan's 48 remaining operational reactors are safe enough to reopen.

Spectrum's rigorous coverage of nuclear issues has not gone unnoticed. That 1979 Three Mile Island issue, proposed by Christiansen, with articles by Rubinstein and Christiansen and editing mostly by Rubinstein, won *Spectrum*'s first National Magazine Award, the highest honor in U.S. magazine publishing. And a 2011 article by Strickland about Fukushima–a blow-by-blow account very similar in its wealth of detail to Rubinstein's Three Mile Island story–was a pillar of our fifth such award, in the category of "General Excellence."

More important, these stories give engineers and other tech-savvy people the kind of information they want on events of enormous import. Speaking of Christiansen, who was an engineer before becoming a publisher, Rubinstein says: "He realized that a lot of journalism in the technology and science world was about what goes right. He knew that you can often learn a lot more by studying what went wrong."

—GLENN ZORPETTE

CORRECTIONS: A Fun Fact for the article "4G Gets Real" [January 2014], misstated the size of a typical movie file. It is 800 megabytes, not 800 megabits.

The article "Virtual Reality's Moment" [January 2014] mischaracterized the Irvine, Calif., location of Oculus VR as part of Silicon Valley. Irvine is in Orange County, not Silicon Valley.

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NEWS

68 PERCENT: SHARE OF THE POPULATION OF SUB-SAHARAN AFRICA WITH NO ACCESS TO ELECTRICITY

TONY KARUMBA/AFP/GETTY IMAGES

AFRICA POWERS UP

The Obama administration's $7 billion project to electrify sub-Saharan Africa begins

NIGHTTIME NEAR NAIROBI: Only 18 percent of Kenyan households have access to electricity.

This spring, construction is set to begin on the first projects coordinated through Power Africa, a multibillion-dollar Obama administration initiative that seeks to double access to electricity in sub-Saharan Africa within five years, and in some cases accelerate reforms in the governments of the nations involved. Among the initial projects are wind farms in Kenya and Tanzania, and a solar project in Tanzania.

More than two-thirds of the 800 million people in sub-Saharan Africa have no access to electricity. Announced last summer, Power Africa is coordinating efforts among U.S. government agencies and private investors to try to reduce that number. The effort initially focuses on six countries: Ethiopia, Ghana, Kenya, Liberia, Nigeria, and Tanzania. The goal is to add 10 gigawatts of electricity generation capacity, which should increase electricity access by at least 20 million households. The U.S. government will provide more than US $7 billion in financial support and loan guarantees, as well as the support and expertise of 12 U.S. government agencies. Private investors have committed more than $14 billion in loans, loan guarantees, and equity investment, according to the White House. »

The amount is small compared to developed-world standards: The U.S. electric power industry had capital spending of $90.5 billion in 2012, according to the Edison Electric Institute. And it is a drop in the bucket of what's needed. "Power infrastructure in sub-Saharan Africa suffers from massive degrees of underinvestment as compared to the developed world," says Andrew Herscowitz, coordinator for Power Africa. According to the International Energy Agency, sub-Saharan Africa will require more than $300 billion to achieve universal electricity access by 2030. Nevertheless, the investment would be a significant improvement. According to figures from the World Bank, the six countries have averaged a combined investment of just over $3 billion a year in their electricity infrastructure.

The White House touts the initiative as a new model of foreign aid. Rather than just giving grants and loans, Power Africa is aimed at fostering collaboration among U.S. government agencies and corporations in an effort to increase private investment that could lead to better access to electricity. "We're taking all our tools and working together on common goals," says Herscowitz. For example, Tanzania's standard power purchasing agreement was for 15 years, but in order to obtain financing, one solar power deal needed a 20-year agreement. Power Africa helped convince the government to make a 25-year deal, he says.

"At the same time, we're trying to use these [financial] transactions to push key reforms that will stimulate more private sector investment in these countries," says Herscowitz.

What are the key reforms? It depends on the country, but few doubt that widespread corruption has inhibited investment in the past and could continue to do so. Herscowitz says that where corruption is a problem, Power Africa is pushing for greater transparency.

Nigeria is an example of both the progress and the challenges. In that country, "massive, widespread, and pervasive corruption affected all levels of government," according to a report by the U.S. State Department. But the Nigerian government, now a democracy, has made progress in privatizing its power industry. Paul Hinks, CEO of U.S.-based Symbion Power, which is involved in several Power Africa projects, says Nigeria "is probably going to become a model for the rest of Africa" in that regard. In one Power Africa project, 15 companies plan to participate in this privatization program, according to the White House.

The "unique political environment" in some countries is one of the main challenges for private investors, says Bob Chestnutt, a project director with Aldwych International. This London-based boutique firm develops power projects focused on sub-Saharan Africa. In Kenya, for example, both President Uhuru Kenyatta and his deputy president, William Ruto, are charged with inciting violence that killed at least 1300 people in the wake of a disputed election in late 2007. If the trial in the International Criminal Court goes forward, it could destabilize the investment environment within Kenya, says Chestnutt.

Hinks, who is also chairman of the nonprofit Corporate Council on Africa, admits that corruption is a problem but asserts that's no reason not to invest. "You can do business in Africa without getting involved in corruption," he says. "A lot of U.S. companies say they don't do business in Africa because of corruption. But those same companies do business in… other places where there is also corruption."

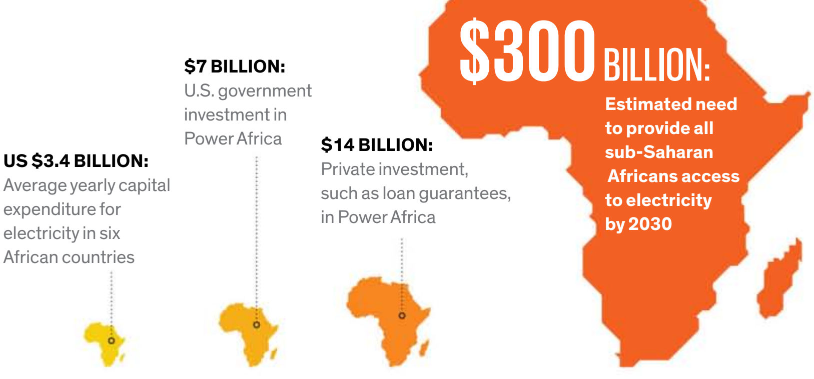
The other big challenge for expanding electricity access in Africa is logistical, says Chestnutt. The places with the least access are in rural, remote areas. Aldwych is planning two wind farms under the Power Africa initiative–one in Tanzania and one in Kenya. The company hopes to start construction on a 300-megawatt installation at Lake Turkana, Kenya, in April. However, it's located "in a barren desert wasteland. It's 1200 kilometers from the nearest port, and the last 200 km of roads will need to be upgraded," explains Chestnutt.

Such logistical problems are why Power Africa has a strong focus on off-grid and minigrid projects and on using renewable energy sources. For example, General Electric and the U.S. Africa Development Foundation launched a competition, called the Off-Grid Energy Challenge, to encourage African individuals and companies to come up with innovative approaches to generation and distribution. In the first contest, held last fall, three Kenyan and three Nigerian groups were awarded grants of up to $100 000 to develop their projects.

At this stage Power Africa is focused more on measuring the closing of financing deals than on the start of construction. As of February, 26 deals were in the works for projects that could provide 5.2 GW of electricity. Power Africa officials expect to have 4 GW reach "financial close" by the end of the year.

At the very least, Power Africa has served to stoke interest in the continent by U.S. companies and investors. "Power Africa has prompted a sea change in the attitude of U.S. institutions," says Chestnutt. "There is much more focus and drive coming from the United States because of this initiative." —TAM HARBERT

POWER AFRICA IN PERSPECTIVE



ELECTRIC LIGHT ORCHESTRATED? Alas, even if we took control of the Van Allen belts, it probably wouldn't result in more auroras.

SARA WINTER/GETTY IMAGES

CAN WE HACK THE VAN ALLEN BELTS?

An audacious scheme could silence Earth's satellite-killing radiation

The radiation belts around Earth are loaded with dangerous protons and electrons that can damage spacecraft. Now researchers are launching experiments to see if they can clear away the high-energy particles that pose the hazard by blasting them with radio waves.

When humans began exploring space, the first major find was the Van Allen radiation belts, doughnut-shaped zones of magnetically trapped, highly energetic charged particles. The Van Allen belts consist mainly of two rings: The inner belt starts roughly 1000 kilometers above Earth's surface and extends up to 9600 km, while the outer belt stretches from about 13 500 to 58 000 km above Earth. The location and shapes of the belts can vary, and they can even merge completely.

High-energy protons are found within the area of the inner belt, whose size remains generally stable over the course of years to decades. The outer belt, on the other hand, is home to high-energy electrons and can vary dramatically in size and shape over the course of hours or days.

The huge amounts of radiation in the Van Allen belts can pose major risks for the host of satellites that pass through or orbit within these swaths of space. There are ways to make spacecraft more resistant against this radiation. For instance, spikes on their surfaces known as electron emitters can radiate away excess lower-energy electrons that might otherwise accumulate and cause a spark. In addition, shielding can help keep high-energy protons and electrons from penetrating nonconducting materials and building up inside them, which could lead to a damaging discharge.

However, decades of models and observations suggest a more dramatic solution: using carefully tuned electromagnetic waves to drive these particles out of space and into Earth's atmosphere. Scientists first explored the idea of dispersing electrons in the outer belt, and they are now targeting protons in the inner belt.

"It's really mind-boggling to think there could be human control over such huge volumes of space," says Jacob Bortnik, a space physicist at the University of California, Los Angeles. "On Earth we control nature all the time, like building dams, but the prospect of doing it in space is fascinating–it seems a bit like science fiction."

One radiation-clearing strategy involves using very large radio transmitters on the ground to beam very low frequency (VLF) waves upward. These can in principle interact with and scatter charges in the radiation belt and drive them into the upper atmosphere.

"The result would be a little bit like auroras, although you wouldn't see them," Bortnik says.

The problem with that approach is getting VLF waves through the ionosphere, the layer of the atmosphere that sits about 80 to 640 km above Earth. "That layer is very conductive, so it's hard to get signals through it efficiently," Bortnik says.

Another strategy would station satellites that emit VLF waves in the radiation belts. "The problem is that you'd need quite a lot of energy," Bortnik says, and large antennas that would be challenging to fit onto spacecraft.

Still, Bortnik points out, the U.S. Air Force's Demonstration and Science Experiments (DSX) satellite, set for launch in 2016, will carry an instrument to monitor the effects that VLF waves broadcast in space might have on these dangerous electrons. "Those experiments can show how well VLF waves actually do, and maybe change what

NEWS

we think we know about what is needed to clear away electrons," Bortnik says.

Initial efforts to clear the Van Allen belts targeted electrons because they tend to get trapped there as the result of high-altitude nuclear explosions. In 1962, a U.S. high-altitude nuclear weapons test named Starfish Prime generated a highly energetic artificial electron belt that disabled the first commercial communications satellite, TelStar 1, so researchers sought ways to protect spacecraft from nuclear weapons used in space.

However, it's the protons in the inner belt that scientists have recently explored. Getting rid of them would potentially open up valuable new orbits for satellites and make travel safer for astronauts, says Maria de Soria-Santacruz Pich, whose Ph.D. work at MIT was on manipulating the Van Allen belts. It might also be impossible.

"Protons are heavy, about 2000 times heavier than electrons, so if you imagine a proton bashing into a piece of silicon, it can do a whole lot more damage than an electron," Bortnik says. "Clearing them out would be good."

Pich and her colleagues discovered that a type of VLF electromagnetic wave known as an electromagnetic ion cyclotron (EMIC) wave could potentially disperse protons in the inner belt. Pich says this strategy poses no hazard to Earth—the swarm of protons would be virtually unnoticed in the atmosphere.

Pich and her colleagues recently refined the computational strategy needed to figure out what frequencies space-based antennas should use and how much power is needed. However, Pich also found that to disperse all the protons from the region, you'd need a million 15-meter antennas operating for a few years, "which is indeed not feasible in the near future," she says.

Nonetheless, Pich noted, her calculations assume that the waves these antennas generate do not bounce back and forth inside the inner belt. If they do, that could greatly improve their effectiveness, potentially making the strategy possible. A satellite mission would decide the matter one way or another, but there's a lot of engineering work needed to even propose such a mission, she says.

It remains uncertain as to whether removing these radiation belts might have unintended consequences. "At present we don't think there is any downside to not having them, but as with all things geophysical, it is hard to know all the complex interconnections between the various systems and estimate the full effect of removing the radiation belts completely," Bortnik says. "That's the most any of us can really say at the moment."

—CHARLES Q. CHOI

> "It's really mind-boggling to think there could be human control over such huge volumes of space."
> —JACOB BORTNIK, UCLA

THE RISE OF THE MONOLITHIC 3-D CHIP

Dense 3-D circuitry could offer an alternative to miniaturization

Ever since the integrated circuit made its debut, semiconductors have been "single-story" affairs. But chipmakers are now considering ways to build additional transistor-packed layers right on top of the first. The approach—dubbed monolithic, or sequential, fabrication—could boost the density, efficiency, and performance of logic chips without necessitating a move to smaller transistors. And that could be a boon for an industry that is seriously contemplating the end of miniaturization.

The concept of 3-D circuitry is nothing new. Chips are routinely packaged one on top of another. Nowadays, this packaging is increasingly done using large copper pillars—called through-silicon vias, or TSVs—to vertically connect already-completed chips.

But this prefab approach has its limitations. TSV widths can be measured in micrometers, and that scale is gargantuan compared to the nanoscale features in state-of-the-art chips. That size limits the use of TSVs to fairly low-density connections, such as those needed to join memory and logic together.

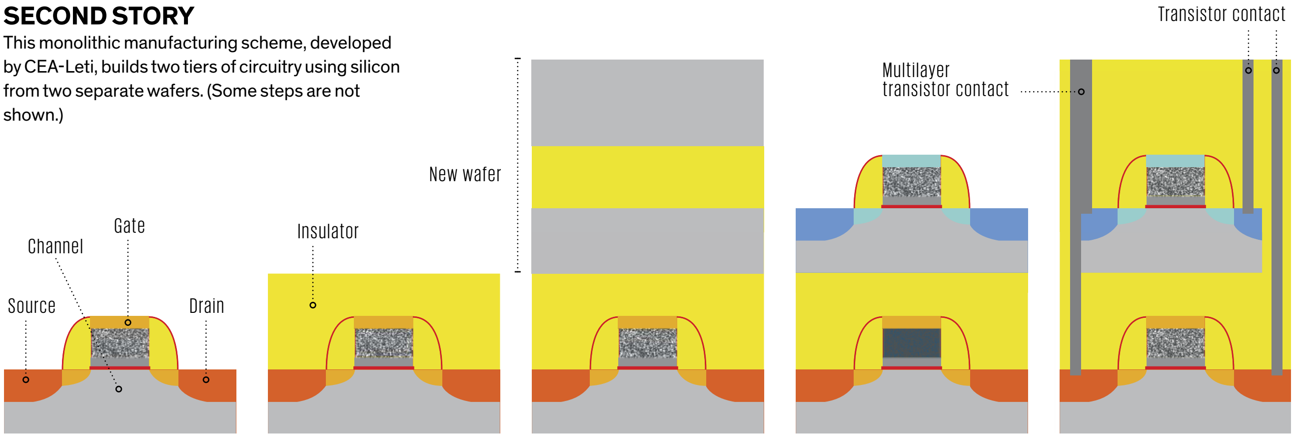
In a monolithic 3-D circuit, a chipmaker would simply continue building on top of a 2-D chip, adding an additional layer of silicon on which another set of circuitry could be built. The vertical connections made in this process could potentially be as dense as those found on a 2-D logic chip. If such circuits could be made, chipmakers might be able to avoid all the technical complications associated with shrinking circuitry. "What you win in terms of density, performance, and power consumption is what you would if you had [moved to the] next generation," says Maud Vinet, manager of advanced CMOS at CEA-Leti, a research institute in Grenoble, France.

But the process is less straightforward than it sounds. Temperatures upwards of 1000 °C are typically used to force dopant atoms into silicon and create the semiconductor portions of the transistor. Applying such heat

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

SECOND STORY

This monolithic manufacturing scheme, developed by CEA-Leti, builds two tiers of circuitry using silicon from two separate wafers. (Some steps are not shown.)



THE FIRST LAYER of transistors—and the metal wires used to connect them—is built on a silicon wafer.

THE CIRCUITRY is coated with a layer of oxide to serve as electrical insulation.

A NEW WAFER containing a layer of oxide sandwiched between two layers of silicon, one thick and one thin, is bonded upside down on the first layer.

THE BULK of the wafer and oxide are removed, and a second layer of circuitry is built on top of the remaining silicon.

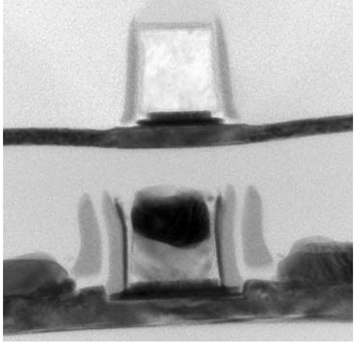
HOLES ARE ETCHED down through the stack and filled with metal. The resulting interconnect can wire two layers together [left] or access each layer individually [right].

to create a second layer of transistors could destroy crucial components in the first, including salicide, a metal-silicon alloy used to help carry signals in and out of devices.

Now, research into lower-temperature processes is picking up. Leti has developed one scheme [see illustration, "Second Story"] that bonds a second silicon wafer on top of the first tier of circuitry. All but a thin silicon layer on this second wafer is stripped away. A second layer of transistors is built using a process called solid-phase epitaxy, in which a mixture of dopant atoms and amorphous silicon is laid down. The mix is then heated to just 600 °C, giving the silicon enough energy to crystallize. As a last step, connections are made by etching holes down to the first layer and filling them with copper.

This approach has been used to create basic circuits, such as inverters, that span two chip layers. And last year, Leti reported that devices fabricated with this process perform as well as those made at higher temperatures. The work is now getting the attention of chipmakers. In December 2013, during the IEEE International Electron Devices Meeting in Washington, D.C., Leti announced that it had entered into an agreement with mobile chip powerhouse Qualcomm to evaluate the technology for mass production. In the process of this research, Vinet says, Leti worked closely with manufacturing partner STMicroelectronics. "There is no major roadblock to the transfer of this technology to foundries," she says. "I feel very confident when I say that."

Leti isn't the only group exploring monolithic fabrication. At the same meeting, for example, a team led by Jia-Min Shieh of the National Nano Device Laboratories, in Hsinchu, Taiwan, presented two-tier circuits made by growing silicon atop a layer of transistors instead of adding a second silicon wafer. The Taiwan team's low-temperature process isn't sufficient to create perfect single-crystal silicon, so the process might be suitable only for creating memory, which tends to be more tolerant of crystal defects, Shieh says.



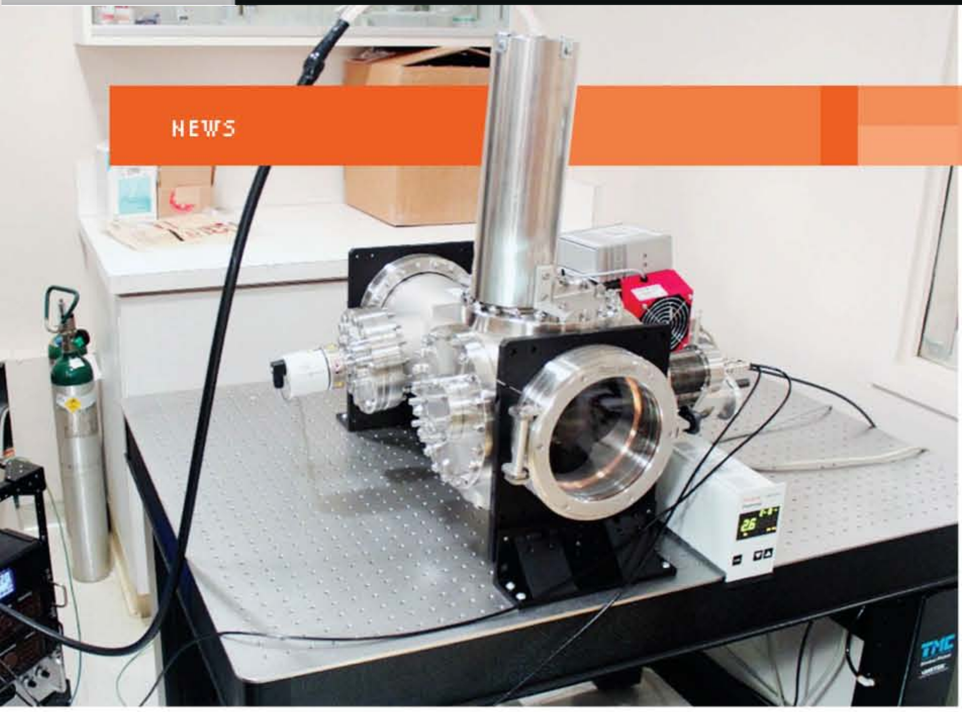
TWO-STORY CIRCUIT: Multistory circuits could let chipmakers increase the density of devices on a chip without having to shrink transistors.

CEA-LETI

When it comes to memory, monolithic 3-D fabrication already seems to be making inroads in industry. In August, Samsung announced it had begun production on NAND flash with memory cells arranged along dense vertical lines, and other companies have similar plans. But details are scant on the particulars of the manufacturing process.

"Memory looks like it's already commercialized. Logic has a long way to go," says Sung Kyu Lim of Georgia Tech. Lim, who is working on monolithic 3-D circuit design, says there are open questions that can be resolved only when research progresses from simple components to full-size chips. Manufacturing imperfections and variations could lower yield and make monolithic 3-D chips more expensive. He adds that transistors made at lower temperatures may not perform as well as their high-temperature brethren, a shortcoming that would necessitate larger and thus less dense transistors in the upper stages of designs. Still, he says, as chipmakers bump up against fundamental physical limits, they may find themselves short on options. In the future, he says, "the only way to go to add more devices will be vertical." —RACHEL COURTLAND

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



NEWS

EXTREMELY TINY X-RAY: An electron-emitting chip is at the heart of a new type of X-ray source. It can replace large particle accelerators in phase-contrast imaging.

THE MEDICAL X-RAY'S NEW PHASE

Phase-contrast imaging could show more with less radiation

The X-ray that imaged your father's broken leg when he was a kid isn't fundamentally different from the one at your doctor's office today–other than that it's now digital rather than film-based. But the technology is on the verge of a big leap forward that will let doctors see more with less light.

To take an X-ray today of some part of the body other than the bones, a patient needs to ingest a contrast agent like iodine or barium that binds to the tumor or other structure the doctor wants to examine. But contrast agents can be hard on the kidneys, enough to harm or even kill some already weakened patients. And some kinds of X-ray imaging today, like computed tomography (CT) scans, involve such heavy X-ray doses that the patients risk an increased cancer rate just to provide good pictures for their doctors.

Enter a technique called X-ray phase-contrast imaging (XPCI), in which instead of measuring the X-ray's intensity, you measure the change in an X-ray's phase. X-rays move slower when they pass through muscle mass than through blood, for instance. So a chest X-ray wave front that passes through a lung sac (mostly air and blood vessels) will arrive sooner than a wave front that passes through the heart.

XPCI can therefore image not just bones and cartilage but also internal organs, internal bleeding, tumors, and plenty more. Moreover, XPCI involves no toxic contrast agents and a substantially lower X-ray dosage.

"People are getting more and more CT scans. The doctors love them because they can get a better diagnosis, but the radiation dose is getting to be too high," says Mark Eaton, president and CEO of the X-ray company Stellarray, based in Austin, Texas. "Phase-contrast imaging is fundamentally different. What you're detecting is the phase change, not the absorption. It is a profound level of dose reduction, by one to two orders of magnitude."

The catch to date is that XPCI has been available only from extremely powerful, laserlike X-ray sources such as warehouse-size particle accelerators.

Traditional X-ray machines shoot out a range of different X-ray wavelengths from various points and in various directions. XPCI is more demanding. "What you really need is basically something like a laser, but for X-rays," says Luis Fernando Velásquez-Garcia, principal research scientist at MIT's Microsystems Technology Laboratories.

For XPCI X-ray sources, particle accelerators are best. But just as some particle accelerators have been miniaturized onto chips, X-ray sources that were formerly based on particle accelerators have been shrinking too. One of the more promising XPCI developments is a tabletop chip-based system being developed by Velásquez-Garcia and his colleagues at MIT and Massachusetts General Hospital, in Boston.

The researchers have fabricated a chip that contains some 12 100 microscopic electron emitters, each of which spits electrons out of a nanometer-sharp metal tip. The resulting beams of electrons are accelerated by a high-voltage electric field and crash into a thin gold film that emits a nearly monochromatic beam of X-rays.

Stellarray is developing its own XPCI imaging device, which is not unlike the MIT technology, says Eaton, but he would not disclose the device's specifics.

Mark Evans is the CEO of Radius Health, an X-ray company based in Oxford, England, and Los Angeles. He says the vacuum-tube-to-microchip size reduction of next-generation X-ray devices is just as important as the dose reduction. Today's X-ray machines are the size of mainframe computers. XPCI machines could get down to PC size or smaller.

"Most ICUs and ERs are busy places, so positioning this quarter-ton monster takes a lot of time and effort, sometimes half an hour," Evans says. "If you could make it smaller and lighter, you could save a lot of the radiographer's time."

Heinz Busta, of Chicago-based Prairie Prototypes, chairs the steering committee of the International Vacuum Nanoelectronics Conference, which is the leading conference in XPCI and miniaturized X-ray sources. He says he's seen a rapid increase in interest in XPCI recently, and that engineers in China, Europe, Japan, and South Korea are working on shrinking XPCI sources as well. "For nondestructive testing, sterilization, homeland security, medical imaging, there are huge applications," he says, "and not only new applications but safer applications." –MARK ANDERSON

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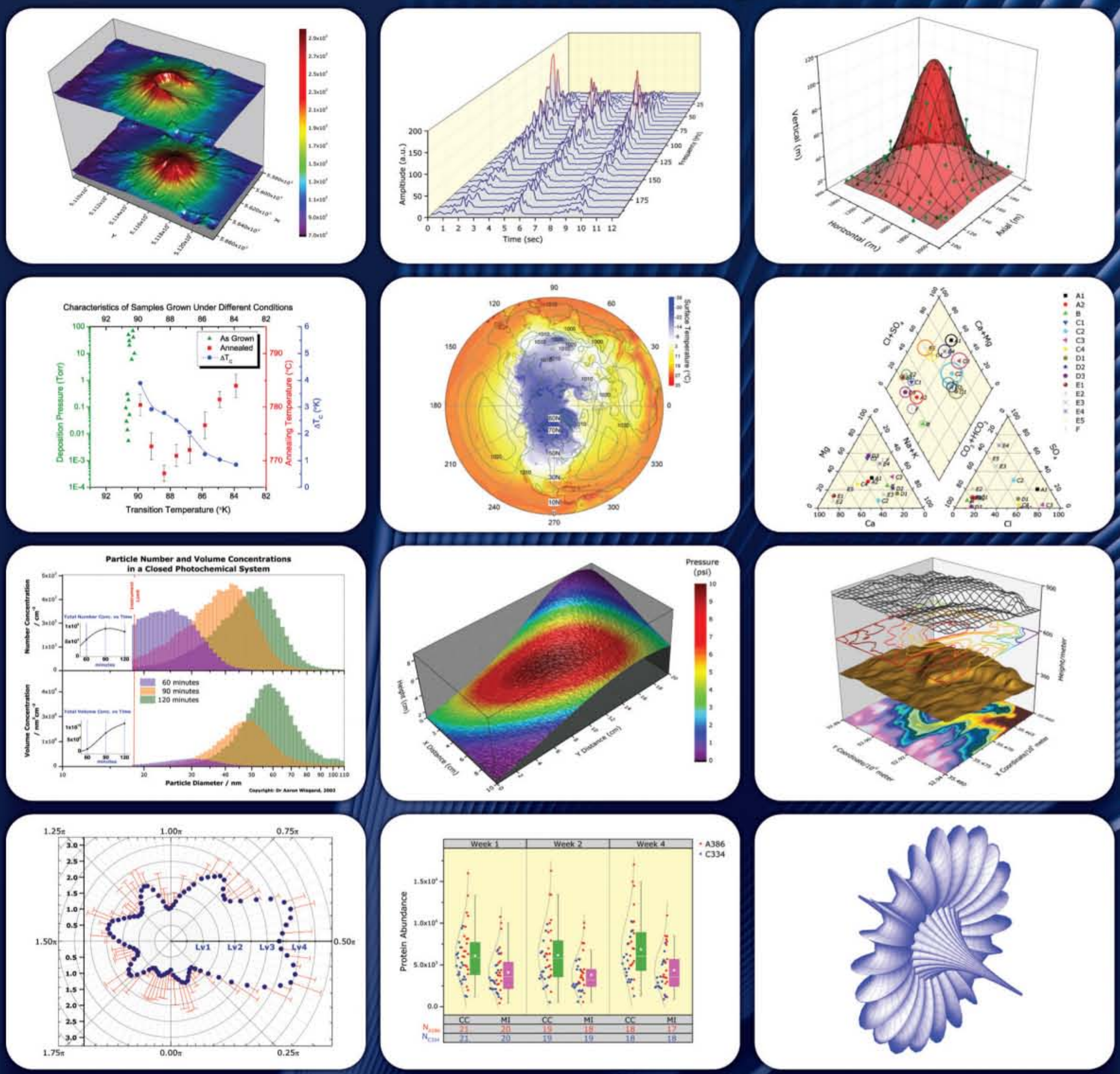

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IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

ICARUS REVISITED

Swiss psychiatrist and adventurer Bertrand Piccard made the first-ever nonstop trip around the globe in a balloon 15 years ago. Here he is shown inside a replica of the cockpit in which he'll be stationed when he attempts to circumnavigate the globe in a solar-powered airplane in 2015. The photo was taken on 17 December, just before the start of a 72-hour simulation of a segment of the 25-day trip. The aim of the test was to prepare Piccard for the demands of the flight in the lightweight Solar Impulse HB-SIB aircraft. The test gauged how well he adjusted the plane's flight path to catch the sun's rays during the day and how well he used stored energy at night. This data will also be used to determine how he'll likely respond to fatigue and stress.

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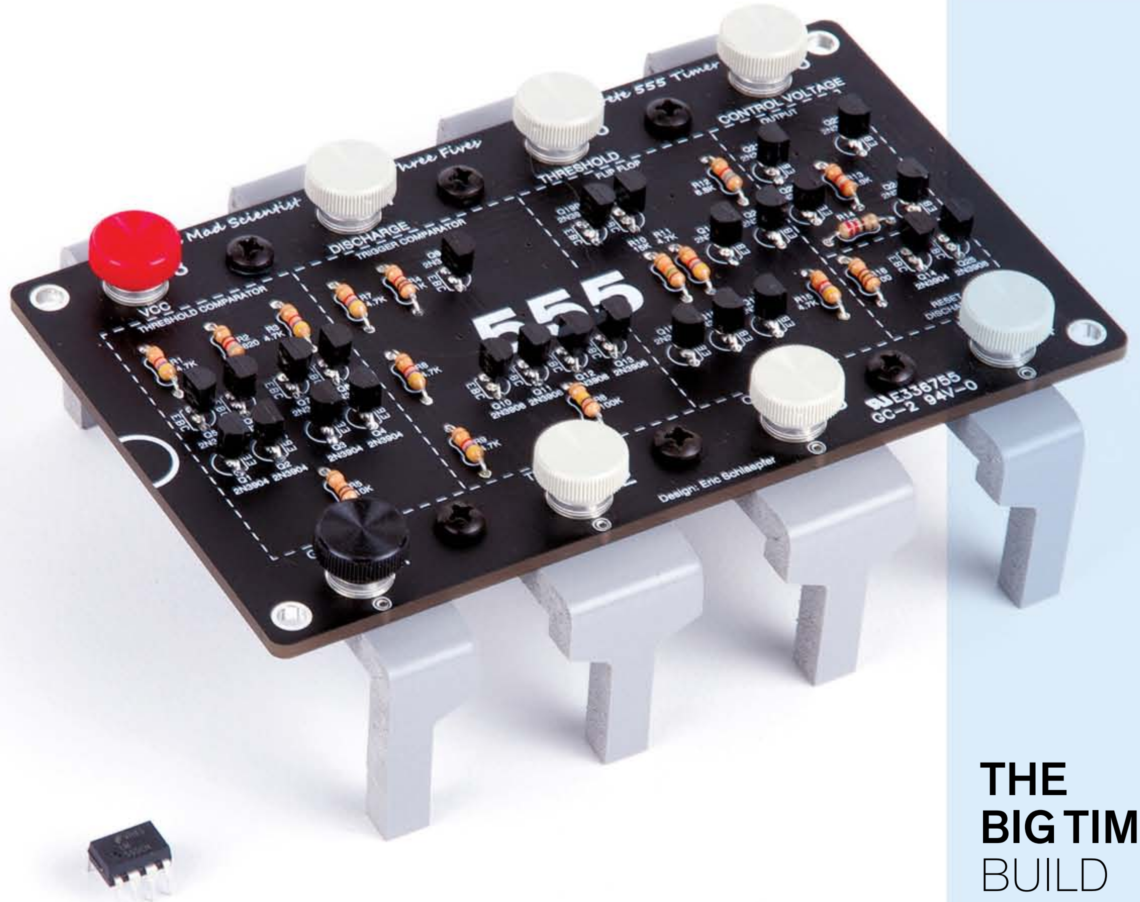
NUMBER OF 555 CHIPS PRODUCED ANNUALLY, ACCORDING TO HANS CAMENZIND, WHO DESIGNED THE IC IN 1971



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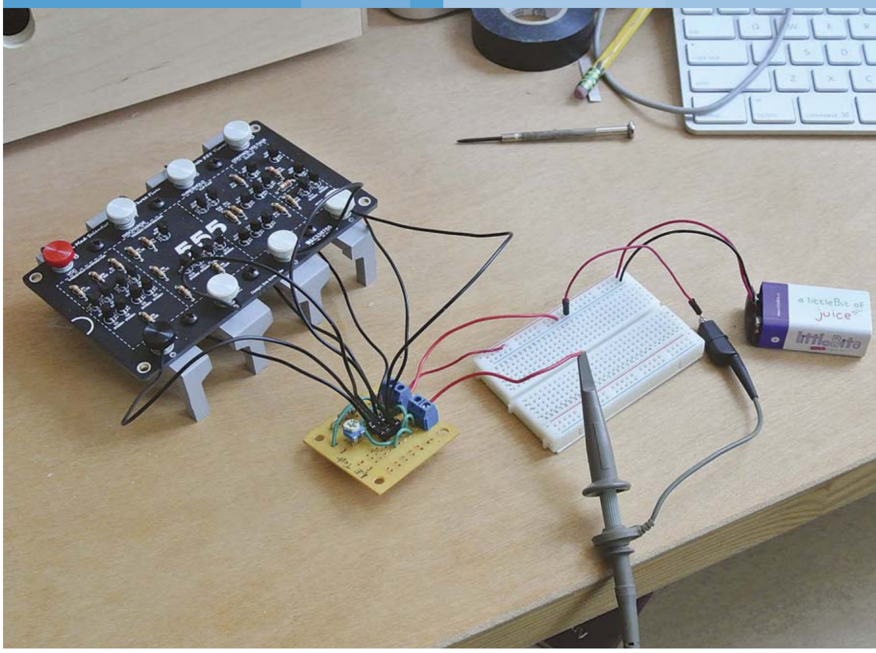
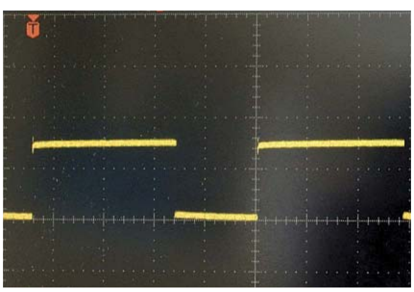
RESOURCES_HANDS ON

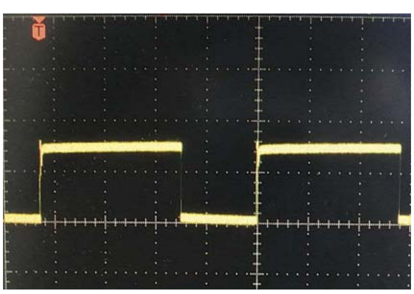
THE BIG TIME

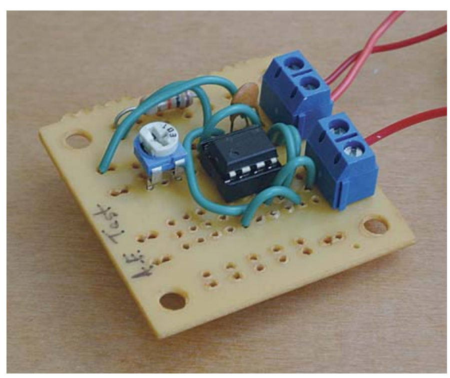
BUILD A GIANT VERSION OF THE 555 TIMER IC

Biologists have plastic DNA helices, astronomers have celestial globes, and chemists the ubiquitous periodic table wall chart. These iconic objects each encapsulate a foundational piece of working knowledge, recognizable to all practitioners in a field. Sadly, such touchstones are thin on the ground for electrical engineers. Although pretty, vacuum tubes, for example, are a niche technology these days, while the transistors and integrated circuits that define the discipline are a bit on the small side for easy viewing. So I was pleased when I learned about the recent creation of the US $35 Three Fives Discrete 555 Timer Kit, sold by Evil Mad Scientist, a DIY and open-source hardware company located in Silicon Valley. • The Three Fives kit is a working model of the 555 integrated circuit. It's hard to think of an IC more ubiquitous than the 555 timer, which was introduced in 1971. There can't be an electrical engineer alive today who hasn't used a 555 at some point, for tasks ranging from simply making a light blink on and off to pulse-width modulation; in January's Hands On article, our contributor used the 555 to make a music organ with conductive ink traces. Unlike many other chips that have come and gone over the decades, the 555 is still finding its way into all kinds of prototypes and products, with no end in sight (for the origins of the chip, see "25 Microchips That Shook the World," *IEEE Spectrum*, May 2009). Just as DNA models, star maps, and periodic tables serve as reminders of fundamentals that can get obscured by day-to-day minutiae, so too the Three Fives kit is a reminder that even the most complex digital processor is still at its heart just a collection of very simple components. • When assembled, the Three Fives stands 4.3 centimeters high, 9.9 cm wide, and 13.25 cm long, compared with the measurements of a typical 555 IC: 8.38 millimeters high, 7.87 mm wide, ▸









DROP IN, TURN ON: A test circuit I'd previously constructed [above] uses a 555 IC to generate a square wave [top left]. Replacing the IC with the Three Fives model, made of discrete components [top], via leads poked into the IC socket produced an almost identical waveform [bottom left].

and 10.16 mm long. The legs that come with the kit are purely cosmetic, but not so the board that takes the place of the standard ceramic packaging. Much sturdier than a typical printed circuit board, this board doesn't replicate the internals of a 555 IC in every detail. However, it's divided into areas that do correspond to the functional blocks that make up an actual 555, such as the threshold comparator or the flip-flop that's the cornerstone of the timer's operation.

Populating the circuit board with its 26 transistors (split evenly between *npn*- and *pnp*-type) and 16 resistors is a straightforward bit of soldering. Threaded screws accommodate leads to connect the Three Fives kit to the rest of a circuit (there are also holes provided for soldering leads permanently to the board).

The kit is designed to be a "drop-in" replacement for the 555 chip in existing circuit designs, with the caveat that an extra resistor is needed for one pin in some circuits operating above 6.5 volts. After building the trial circuit suggested in the kit instructions—an LED blinker—I tested this drop-in idea with a small 9-V audio-frequency generator I'd built some time ago for troubleshooting circuits. Controlled via a variable resistor, the generator produces square waves between 5.5 and 7.3 kilohertz.

Using my oscilloscope, I measured the generator's maximum and minimum output with its normal 555 chip, and then pried the chip out of its socket. With leads running from the Three Fives kit poked into the bare socket holes, I reran the measurements. The frequency of the output between the chip and the kit matched, as did the shape of the waveforms, albeit with a tiny bit more "ringing" with the kit when the waveform went from a low to a high state.

The 555 kit would be an excellent introduction for electronics beginners learning how to solder—detailed instructions and soldering tips are given in the accompanying leaflet—while introducing them to the basics of integrated circuit design and use.

It also offers opportunities for more advanced students, by exposing the internal components of what's normally a black box (a complete circuit diagram is available on a data sheet you can download from Evil Mad Scientist's website). With an oscilloscope, you can probe each block of the timer as inputs such as the trigger, threshold, and control voltage are varied, demonstrating how they combine to produce various outputs. A useful class exercise might be finding component substitutions or augmentations to optimize this most general-purpose of circuits for specific tasks.

For myself, I hope this opens the door to more kit makers taking integrated circuits out of their black boxes and making them commercially available. The first microprocessor, the 4004, was built from 2300 transistors—no small soldering job, but surely doable over the course of a season. —**STEPHEN CASS**

STEPHEN CASS (4)

IN SEARCH OF NWAVGUY
AN AUDIO ENGINEER CREATED SPECTACULAR DIY DESIGNS—AND THEN VANISHED

SOME AUDIOPHILES SPARE NO EXPENSE TO GET THE VERY BEST sound-reproduction equipment money can buy. They will happily plunk down US $20 000 for a pair of loudspeakers or pay $1600 for one of the more highly regarded preamplifiers. And price tags an order of magnitude higher are not unheard of. ● Expensive stuff looks great and impresses your friends, but does spending more really ensure that you'll get a better product? Blind testing has proved that proposition is no more true for audio gear than it is for wine. Still, many people who manufacture or review audio equipment persist in making subjective judgments, which are often influenced by the price tag. This practice badly irritated an anonymous electrical engineer known to the world only by his online moniker, NwAvGuy. ● Starting in February 2011, NwAvGuy began ruffling feathers in audio circles by strenuously arguing on his blog and other online forums that the only proper way to evaluate audio equipment is to use quantitative blind testing. He used such tests to expose audio gear that had been highly touted in subjective assessments but in fact performed worse than some cheap alternatives.

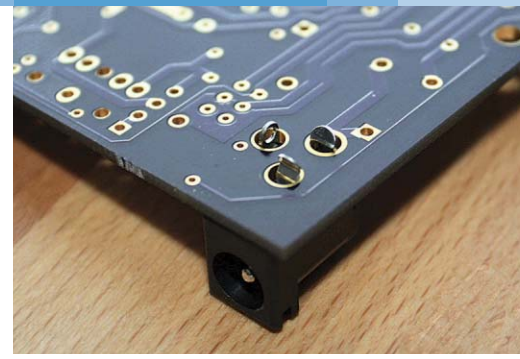
But NwAvGuy wasn't just shouting from the sidelines. He exposed his own skills to critique by presenting an open-source design for a headphone amp that he called the Objective 2 (O2). He created it for people who use full-size headphones with, say, MP3 players, which are typically designed to drive earbuds. On his blog, NwAvGuy boasted that his minimalist amplifier—which can be purchased for as little as $129—"proves you don't need exotic parts or esoteric circuit designs for best-in-class sound, accuracy, and performance."

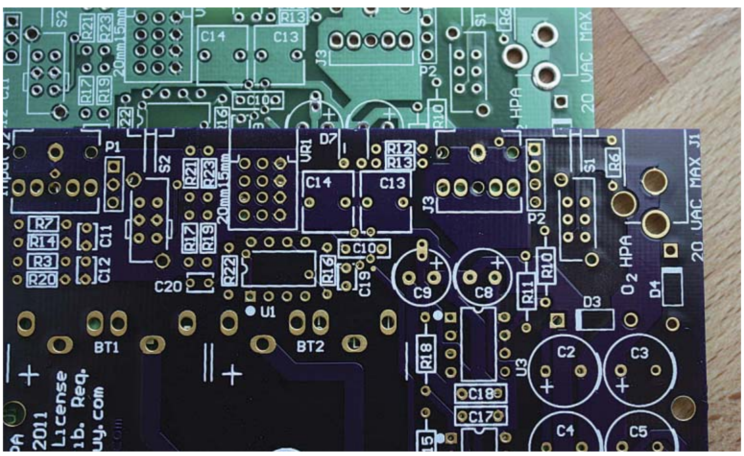
His creation made a splash in the DIY-audio community. People started building his amplifiers using the design documents and detailed notes that NwAvGuy provided online. Then various vendors started producing and selling assembled versions of the O2 amplifier—most prominently JDS Labs in the United States and Epiphany Acoustics in the United Kingdom, whose version won *Hi-Fi World* magazine's Best Headphone Amplifier of the Year award for 2012. "[The O2] was phenomenal," says John Seaber of JDS Labs. "We put it into immediate production."

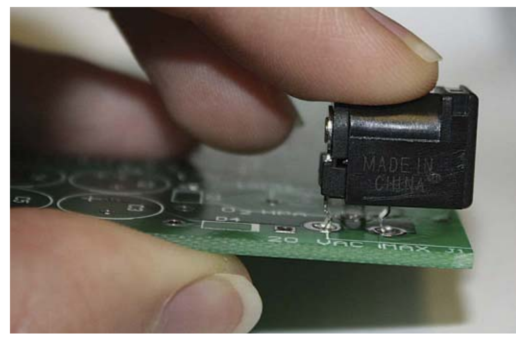
When Seaber first contacted NwAvGuy about his plans to manufacture the O2, he expected a lengthy response from this blogger, who regularly posted 10 000-word essays. NwAvGuy would no doubt want his name all over the assembled units, Seaber thought. But he was surprised by the brevity of NwAvGuy's response, which asked for no such thing. Indeed, he asked for nothing in return. He even made a point of coordinating design changes with Seaber and others who sold his amplifier. "He was basically a free employee," says Seaber.

"I don't want any revenue from the O2," NwAvGuy wrote on his blog, "but I do humbly request everyone please respect the license, which includes proper attribution." But the

ILLUSTRATION BY Brian Stauffer







SOUND REASONING: Buy a finished headphone amp or make one yourself using NwAvGuy's design, which uses through-hole components for easy soldering. Unfortunately, enlarging three holes for the power jack technically ran afoul of NwAvGuy's no-derivatives license.

CLOCKWISE FROM TOP LEFT: EPIPHANY ACOUSTICS; JDS LABS (3)

particular open-source license he applied—Creative Commons CC BY-ND—requires more than just proper attribution: It forbids derivative works. This is different from most open-source projects, which are released with the intent of letting others build on the original, perhaps improving things and, in any event, ensuring that useful designs will not languish if the creator goes bankrupt, loses interest, or otherwise moves on.

This wasn't a problem while NwAvGuy remained engaged with the people building his designs, which grew to include a digital-to-analog audio converter board. He designed the converter in collaboration with George Boudreau, who runs Toronto-based Yoyodyne Consulting. NwAvGuy kept his identity secret even from Boudreau, who has some guesses as to why: "He said he had received e-mail threats." Boudreau also speculates that NwAvGuy might not have wanted an employer to know about his moonlighting.

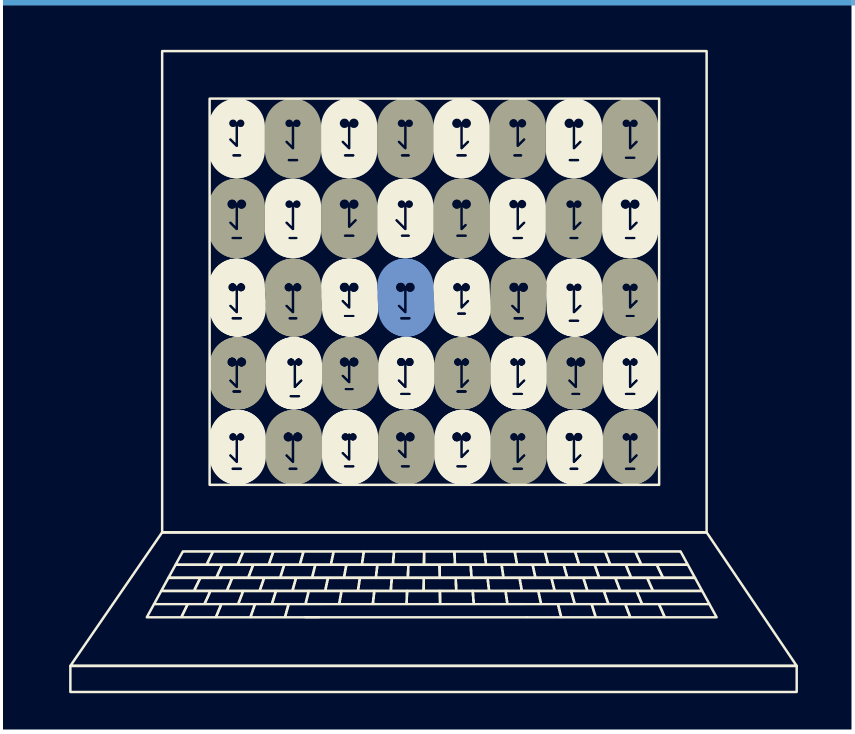
But in July 2012, NwAvGuy went silent. E-mails weren't returned, and blog posting ceased. "He had gone quiet before—for a month or so," says Boudreau. But no one has heard a peep from NwAvGuy in more than a year and a half.

It was always NwAvGuy's prerogative to stop blogging or giving advice. But his mysterious disappearance created a predicament when the power jack used in the O2 amplifier went out of production. Equivalent replacements remain easy to source, but they don't fit the holes in NwAvGuy's original printed circuit board.

"He made it so you could see it, but not touch it," says Seaber. That is, while Seaber and others had the files they needed to have printed-circuit boards made, no one but NwAvGuy had the original layout file, which would allow easy changes. So even after Seaber had wrestled with the thorny ethical and legal issue of whether to modify the board—which he decided was okay in this case because it didn't violate NwAvGuy's fundamental intent—he had to figure out how to make the changes. Fortunately, the only thing needed was to increase the diameter of three holes, which with a little sleuthing through one of the manufacturing-control files Seaber was able to do.

Why didn't NwAvGuy allow derivative works? "NwAvGuy was ripping manufacturers apart left and right," says Seaber. "He didn't want to see tweaked versions of his designs" that didn't perform well. Reasonable enough. But it's unclear what will ultimately become of this immensely successful open-source project if nobody else can become its steward in NwAvGuy's absence.

The bigger question: Has NwAvGuy stopped communicating with others for reasons of his own, or could he have been hit by a bus, as they say? One hint comes from the fact that the domain name registration for NwAvGuy.com was renewed in March 2013, eight months after he stopped communicating, which suggests he didn't suffer some terrible accident or illness. If the mystery engineer is alive and well, he'll presumably renew his domain again this March as well. Or perhaps that's too much of an assumption to make about this Scarlet Pimpernel of the DIY-audio world. –**DAVID SCHNEIDER**



THE ANSWER MACHINE

Who is the crowd?

A FRIEND SAID SHE HAD AN INTERNET QUESTION FOR ME. "Sure," I said, thinking I would have to explain some technical matter in simple terms. • "Who puts all that stuff on the Internet?" she asked. • I stifled a small laugh, uncertain whether or not this was said in jest. But she was serious, and as I have thought about it since, it is actually quite an interesting question. I never cease to be amazed that almost everything I need to know can be found on the Internet. If I have a question, need to fix something, have some problem–whatever–someone has gone to the trouble of posting relevant advice. Yet I myself have put very little out there, and whenever I consider doing so, I discover that it has already been posted. So where do all of these postings come from? • I remembered a short story by Isaac Asimov that I read many years ago about a researcher who set about trying to find where jokes come from. He observed that no one he knew had ever created a joke, yet thousands of new jokes circulated every day. In the end the researcher discovered that jokes were being created by aliens as a kind of psychological test for humans. • I look at my computer screen and imagine all the murmuring voices behind it, clamoring for attention. There is almost a mystical presence out there, not from aliens but from something almost as thrilling and unexpected–a new presence that has been brought about as a consequence of the enveloping architecture of the Internet. • Before the Internet, two complementary networks spanned the globe–the telephone networks with their one-to-one architectures and the broadcast networks with their one-to-many architectures. I thought it would always be that way, but the Internet combined both of these paradigms while enabling a new communications paradigm of "many-to-one." When the number of users was small, this didn't seem very significant, but as the number of users swelled to a billion, emergent properties developed. The "many" became known as the "crowd," and as users we became both members and beneficiaries of the power in that crowd.

The crowd has wisdom, knowing things that may not be known to individuals. It has sentiments, beliefs, and feelings that can be abstracted and analyzed. Moreover, it has the power to affect the real physical world through such actions as crowdfunding and crowdsourcing. Small armies of volunteers and paid contributors can be assembled on a moment's notice to work on projects. For example, Kickstarter helps fund small- to midscale creative projects, Amazon's Mechanical Turk recruits participants to work for very small amounts of money on human intelligence tasks, such as labeling pictures, while Kaggle assembles teams of statisticians to work for larger prizes on data analysis problems, like airline routing optimization. There has even been research on combining real-time crowd input with computer processing to implement "crowd-powered" systems, the initial example being a crowd-powered word processor.

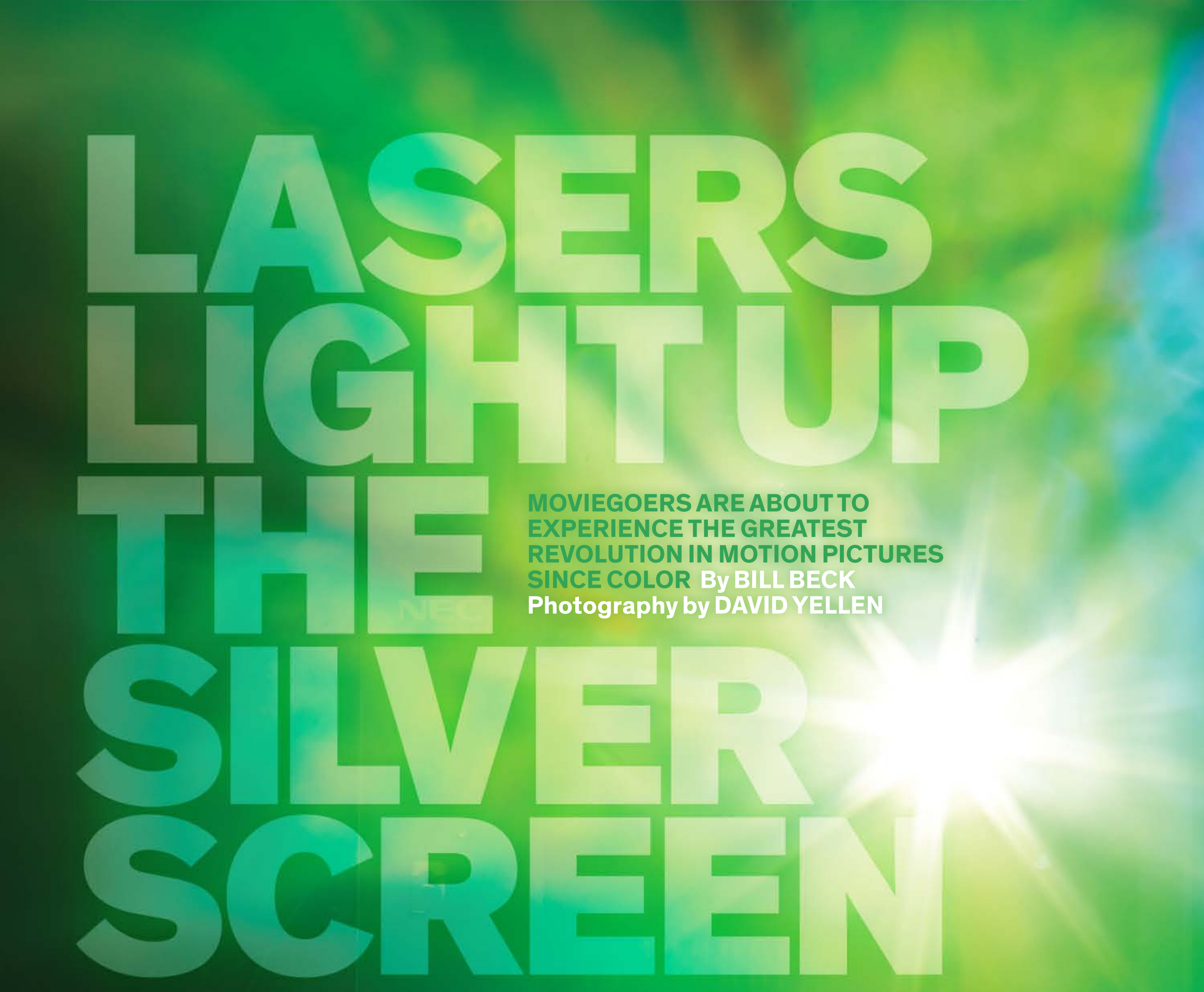
At a recent meeting someone asked whether it would be possible to create "IBM for a day." The question wasn't quite serious, but it invites speculation about future potentials. Today we have flash crowds, but could we also have "flash companies"? Maybe we have them already, since new phenomena are constantly arising out of the mist and then taking a while to be noticed and popularized.

There are individuals out there in the crowd too–lots of them. It reminds me of the old Bell Labs, where there was an expert on anything you needed to know right down the hall. That business model is long gone, but now the equivalent exists on the Internet. Whatever the subject is, there is someone out there in the crowd who knows more about it than you do. Guaranteed.

But I still don't have a simple answer to the original question. It's complicated. ■

ILLUSTRATION BY Greg Mably

LASERS LIGHT UP THE SILVER SCREEN



MOVIEGOERS ARE ABOUT TO EXPERIENCE THE GREATEST REVOLUTION IN MOTION PICTURES SINCE COLOR

By BILL BECK
Photography by DAVID YELLEN

WHEN WAS THE LAST TIME YOU SAW A MOVIE IN A THEATER? Three months ago? A year? Longer than that? • That's the problem. • The movie industry is among the world's most important businesses. The Motion Picture Association of America says that films produced in the United States alone pulled in US $34.7 billion in worldwide box-office revenues in 2012. And yet the industry is beset by a dismaying trend: More and more, people are watching movies on their laptops, tablets, and smartphones. In wealthy countries, middle-class homes are now typically outfitted with huge flat-panel TVs and powerful surround-sound audio systems. The upshot is that for many people, particularly middle-aged ones, a trip to a movie theater is becoming a rare event, if not an increasingly distant memory.

THE MOTION-PICTURE INDUSTRY IS FIGHTING BACK, THOUGH—WITH TECHNOLOGY.

There's a huge push today to develop sophisticated systems that will ensure that the theater experience remains far superior to anything you can get at home or while watching a small screen. These systems will foster the continued growth of 3-D motion pictures, as well as a gradual migration to movies with a higher frame rate, higher spatial resolution, deeper contrast, and even a vastly greater color palette than today's films.

The upshot is that the next three to five years will see the most significant and the fastest technological transition in the history of motion pictures. For the first time, industry leaders have agreed on the need to go beyond the familiar but optically limited characteristics of film stock and embrace the dazzling capabilities of all-digital motion pictures. At the end of this transition, the optical parameters of motion pictures will for the first time approach the capabilities of the human visual system.

This technological revolution will come from some radical transformations in motion-picture projectors. Since 2000, movie theaters have been switching over to digital projectors. But these projectors continue to rely on a 60-year-old technology: xenon electric-arc lamps, whose brightness fades over time. Even brand new, these lamps are not up to the demands of 3-D movies, especially on larger screens. The movie projectors of the future will replace these lightbulbs with lasers.

Actually, the revolution has already started. In September of 2012, Martin Scorsese's film *Hugo* became the first commercial feature-length movie to be shown publicly with a laser projector. The film was an appropriate choice, because *Hugo* is partly an homage to the early history of cinema. Christie Digital Systems, the world's largest supplier of digital cinema projectors, achieved this milestone at the International Broadcasting Convention in Amsterdam.

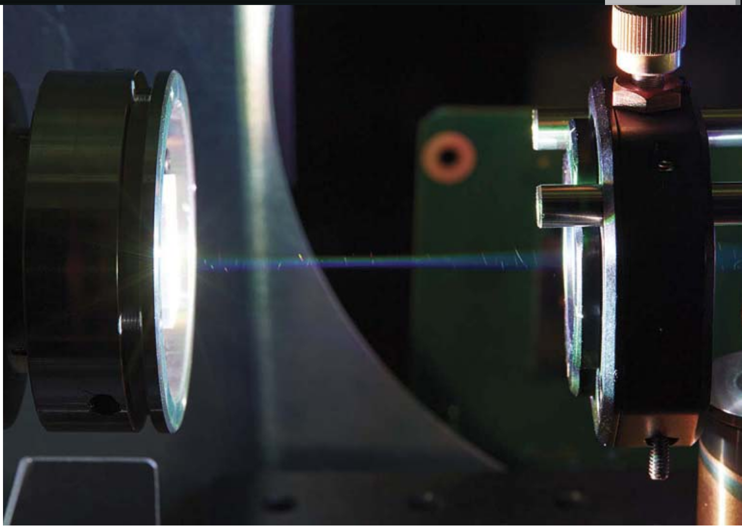
In the United States, Italy, and Australia, theater owners will start installing commercial laser-based projectors in the next several months. Some sales have already been announced. Christie, based in Cypress, Calif., has sold its first laser projector to the historic Seattle Cinerama Theater, which is owned by Paul Allen, Microsoft's cofounder. IMAX, the leading large-screen theater organization, has announced several contracts to convert its 70-millimeter film projectors to laser digital. These systems are scheduled to be shipped in the second half of this year. NEC Display Solutions, which also makes cinema projectors, introduced a laser-based unit for smaller screens at the ShowEast conference this past October. Barco, based in Kortrijk, Belgium, and Sony, the other big players in the cinema-projector market, also intend to introduce laser-equipped models later this year or in 2015. A U.S. company, Laser Light Engines, is working on retrofit kits that will allow technicians to upgrade an existing digital projector by replacing the arc lamp with a laser illumination system. There are more than 100 000 digital theater projectors in the world.

In the larger scheme, these new movie projectors will operate within a globally standardized regime for the capture, encryption, distribution, and exhibition of digital movie content. For more than a decade, the world's movie industries have sought an international standard to guide their transition from 35-mm film to digital. In 2002, the (then) seven major Hollywood studios formed a consortium, the Digital Cinema Initiative, for just this purpose. But such an agreement largely eluded them until 2007, when the first version of the standard, DC28, was finally announced. The most recent version of that standard specifies how current and future projectors will handle and show movies that are breathtakingly more vivid than today's.

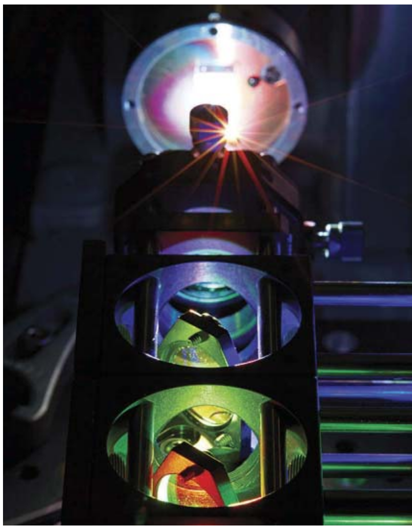
Want to know how these projectors work? Then sit back, relax, and let's get on with the show....

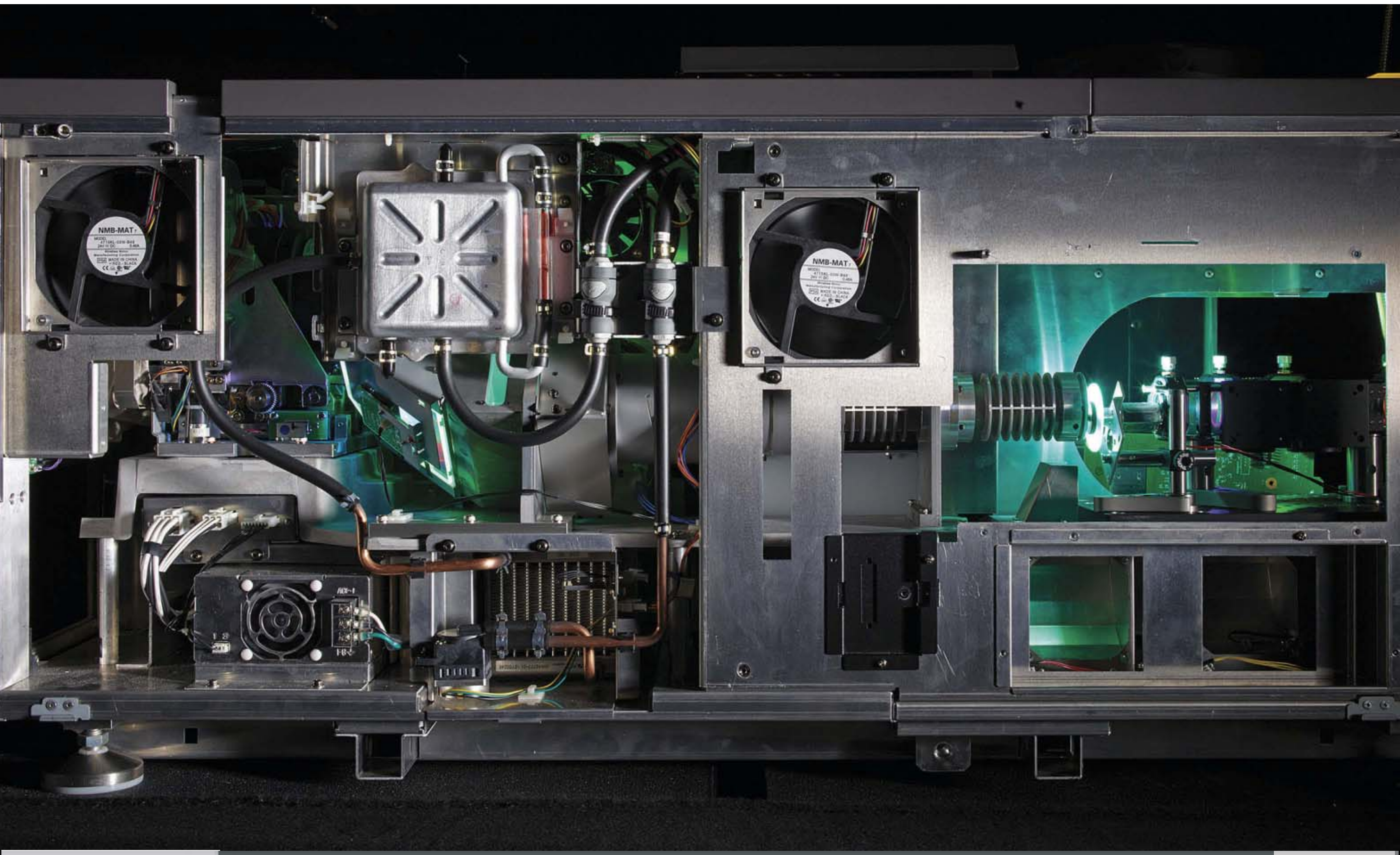
• • •

A TYPICAL DIGITAL CINEMA PROJECTOR costs between $40 000 and $80 000 and is a combination of video, audio, and security components. A typical 2-hour movie fits into a compressed data file of about 150 to 200 gigabytes, which contains the encrypted picture, sound, and other data. A motion-picture projector must do more than turn that data file into a series of color images beamed at the screen at 24 frames per second. It must also be capable of downloading the movie data, which is delivered in encrypted form from the studios to theaters. The most common method of delivery today is on a hard-disk drive, shipped by a courier such as FedEx. At the theater, the digital file is loaded onto a server. The server must store that movie file securely, and the projector must decrypt it and process it for display. The projector must also provide a synchronized output for a variety of multichannel digital sound systems and also for such features as subtitles and tracks for the hearing or visually impaired.



LASER POWERED: Rack-mounted equipment [left] produces the red, green, and blue laser beams that are fed into an NEC NC3240S projector [bottom]. The beams enter through the rear of the unit [bottom, at right] and then go into a color combiner [right], which produces a white beam that enters the back of the projection optics [at left, top photo]. That beam is then separated back into red, green, and blue components, each of which strikes a spatial light-modulator chip that imprints the beam with the moving image.





At the heart of a digital movie projector is something called the image block. It consists of a complex optical assembly of prisms and filters, as well as three spatial light-modulator chips, one each for the red, green, and blue image components. In operation, the optical assembly takes a bright beam of white light and separates it into red, green, and blue beams. Each colored beam has a spectral bandwidth of 40 to 60 nanometers and illuminates its respective chip, which determines, for each pixel of each frame, the amount of light that is sent on to the screen. There the three primary colors combine to make a full-color moving image.

These light-modulator chips are based on one of two competing technologies: Texas Instruments' digital micromirror device (DMD) and Sony's liquid crystal on silicon (LCoS). TI's DMD chip has millions of tiny mirrors that tilt to deflect light, creating millions of tiny beams, one for each pixel in the image. The timing of their tilting controls the amount of light projected for each pixel during that frame. Sony's LCoS, on the other hand, uses a liquid-crystal valve to adjust the amount of light that gets reflected off the chip for each pixel during the frame. That both light-modulator chips rely on reflection is important because it means that the backs of these chips can be cooled, with either a flowing liquid or air directed by a fan.

Both the TI and Sony chips are capable of projecting colors at 4096 different brightness levels per pixel. This is called 12-bit precision, or 36 bits total for the three primary colors. Thus the total number of possible combinations of the three primary colors is 4096^3, or 68.7 billion colors.

TI's chips are used in movie projectors from Barco, Christie Digital, and NEC, while Sony's chips are used exclusively in Sony's projectors. TI offers chip sets at two different resolution levels: 2048 by 1080 pixels (called 2K) and 4096 by 2160 pixels (4K). Sony offers only 4K.

SO WHY THE NEED FOR NEW TECHNOLOGY? Basically, because of 3-D. Until the late 2000s, the various groups involved in the Digital Cinema Initiative–the studios, the theater owners, and the projector manufacturers–were moving methodically toward a system that would give them acceptable image quality and lower distribution costs. In 2005, the studios and manufacturers rushed two prototype 3-D systems to a small number of theaters, to test customer reactions and promote the new capability. These early systems, which were developed outside of the Digital Cinema Initiative, produced images that were dim in comparison with those of 2-D movies and weren't very popular at first.

But then, in December 2009, along came *Avatar*. James Cameron's record-breaking film convincingly demonstrated 3-D cinema's ability to dazzle audiences and command higher ticket prices. Finally, theater owners had a financial incentive to convert to digital. But the introduction of 3-D was ad hoc and uncontrolled. It was a kind of technological Wild West, with studios and 3-D-system suppliers engaging in shoot-outs that pitted the studios' rollout schedules against the suppliers' efforts to maintain standards of image quality and brightness. Money won over quality. After *Avatar*, these improvised 3-D systems became entrenched worldwide as "good enough" solutions.

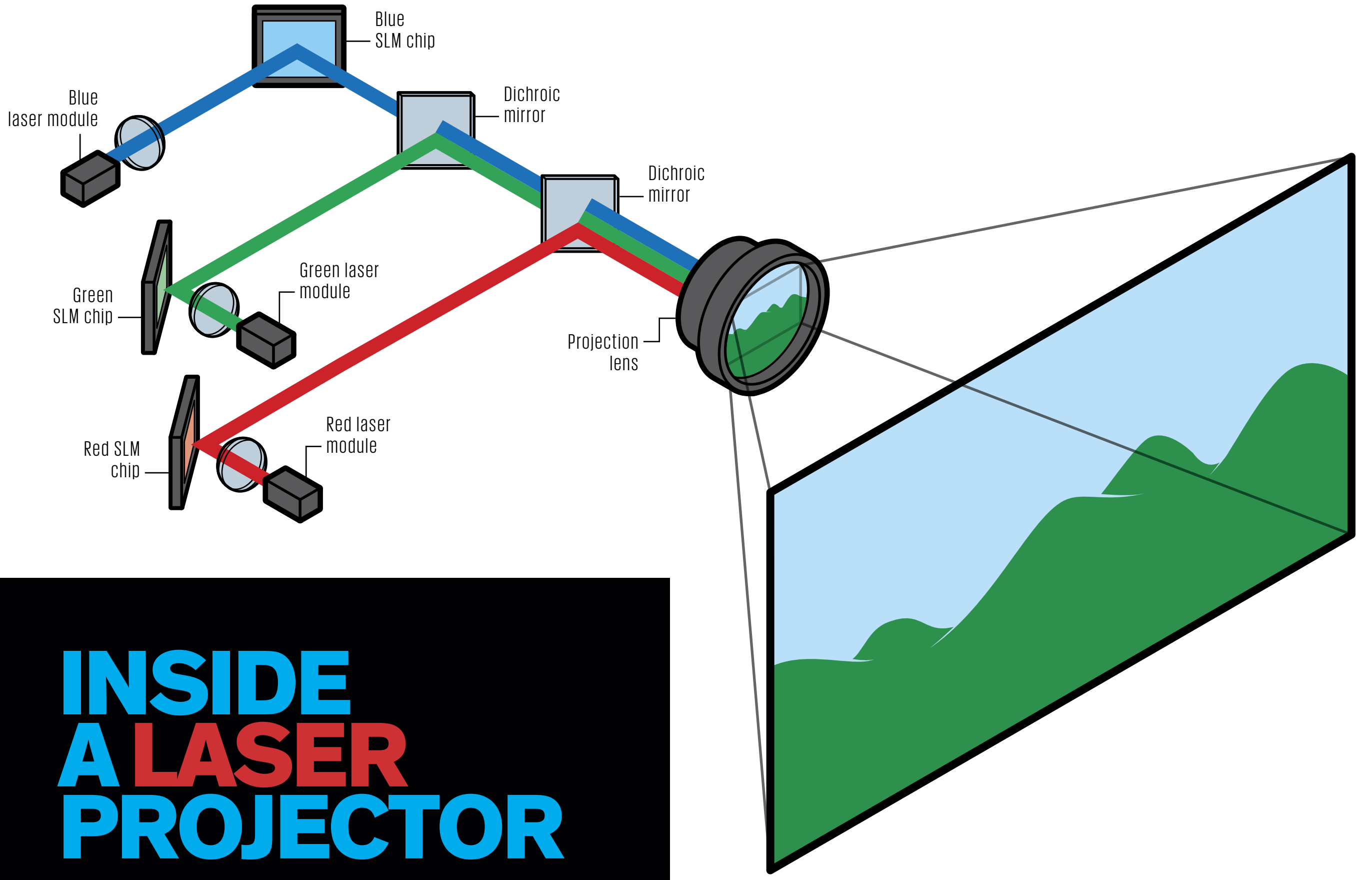
The problem is that on anything except a very small screen, 3-D movies are simply too dim. One reason is that the high-pressure xenon arc lamps used in movie projectors today lose a lot of brightness over time. The brightest digital projectors can emit about 30 000 lumens with a brand new lamp, but this brightness drops to about 22 000 lm after about 200 hours and eventually levels off at something less than 15 000 lm within 800 hours.

What's more, the 3-D technology itself cuts way down on the light. A 3-D projector shows the left and the right eye slightly different views of the same scene. And using a single projector, there are only two ways you can display different left-eye and right-eye frames: You can separate them in time or in space. Projectors incorporating TI chips do the former, and Sony projectors, the latter.

The typical 3-D system developed for TI chips projects alternate left-eye and right-eye images. To portray motion smoothly, the system actually flashes three separate left-eye and right-eye images within the frame period, which is 1/24th of a second. The left-eye and right-eye images are projected with different polarizations. Basically, in a linearly polarized beam of light, the electromagnetic waves vibrate in a single plane. Different polarizations means that the planes are at an angle with respect to each other, typically 90 degrees.

MOVIE PROJECTORS, TODAY AND TOMORROW

PERFORMANCE METRIC	PRESENT: ARC LAMPS	FUTURE: LASERS
PROJECTOR BRIGHTNESS, lumens	Peak: 34 000 Constant: 22 000	50 000 to 100 000
LIFETIME OF LIGHT SOURCE, hours	Large lamp: 300 to 800 Medium lamp: 1000	20 000 to 50 000 (5 to 12 years)
DYNAMIC RANGE, brightest to darkest for each primary color	2000:1	10 000:1
RESOLUTION, pixels per frame	2 211 840 ("2K") or 8 847 360 ("4K")	Up to 33 177 600 ("8K")
FRAME RATE, frames per second	24 and 48 for 2K; 24 for 4K	60 and 120 possible for 2K; 48 for 4K
COLOR GAMUT, percentage of gamut visible to people	40 percent	60 percent
EFFICIENCY, lumens per wall-plug watt	4.8	>10



INSIDE A LASER PROJECTOR

RED, GREEN, AND BLUE laser beams each fall upon a separate spatial light-modulator chip. For each of these colors, the corresponding spatial light modulator determines, for every pixel of every frame, how much light of that color gets reflected through the projector optics to the screen. The path length for each colored beam from the modulator chip to the projection optics must be the same, so that the three images focus on the same plane.

In a 3-D projector setup, the polarization is actually circular, but the phenomenon is no less useful for discriminating between two beams of light. In the projector, the alternating polarizations are accomplished with an electro-optical polarizing filter that switches from one polarization to the other with each image flash. The viewer, meanwhile, wears eyeglasses that have corresponding polarization filters, so only the appropriate image reaches each eye. The projector displays images at 24 times 6 (3 for the right eye and 3 for the left)—or 144—flashes per second.

In Sony's approach, both views are projected at the same time and on the same screen. The Sony spatial light modulators can't flash at a rate of 144 per second. So Sony subdivides the 4K chip into two different 2K subpanels, one for the left-eye images and one for the right. Thus in this 3-D system, the left- and right-eye images are 2K wide but only 0.8K tall (some pixels are lost to a guard band). The Sony 3-D projector has two lenses and a polarizing filter in front of each. The images projected to the left eye go through one lens and the right-eye images go through the other. Then the two images move onto the screen, where they are superimposed on each other. As with the TI system, the viewer wears glasses with corresponding polarized lenses.

Both approaches waste a lot of light—not just at the polarizing filters but also at the spatial light modulators. Consider a viewer watching a 3-D movie projected with TI chips: Each eye sees light slightly less than half the time. With the Sony system, the lamp inside the projector illuminates the entire spatial light-modulator chip, but the projector uses less than half the chip's area to illuminate the screen—again, a roughly 50 percent light reduction.

All told, the losses at the projector, including the polarizing filters, are about 75 percent. Then, 20 percent of what's left is lost at the viewer's 3-D glasses. So the overall loss is approximately 80 percent. Even highly reflective screens can't make up for that much loss. And remember, the brightness of the bulb declines with time.

So perhaps it's no surprise that the popularity of 3-D has been declining, with the exception of the recent motion picture *Gravity* (which often kept the screen filled with the blackness of space, making dimness less of an issue).

●●●

WHY NOT JUST MAKE BRIGHTER XENON ARC LAMPS? The short answer is: Because it wouldn't help. Like any arc lamp, projector bulbs throw out light in all directions. And then this white light must be split into red, green, and blue bands, which are focused onto the light-modulator chips inside the projector. These chips

ILLUSTRATION BY James Provost

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

are just 17.5 or 35 millimeters on the diagonal. To make an arc lamp brighter, the bulb itself must become physically larger, including the arc that produces the light. But increasing the size of the arc makes it harder to focus the light onto the chip. In practical terms, we've already hit the wall in terms of getting more light from arc lamps through digital cinema projectors.

Lasers do not share this limitation. All of their power can be easily focused onto a small area, and essentially all of that power is used. That's not the case with white light: After the three primary colored beams are separated from the arc light, the rest of the visible light spectrum, as well as a lot of infrared and ultraviolet radiation, is wasted. It is dumped within the projector, which must therefore dissipate a lot of heat.

Lasers have other advantages, too. They can be very efficient electrically, last 20 000 to 50 000 hours, have near-constant output, and are highly controllable. Also, because lasers are compact and do not get very hot, they can be packaged into a system small enough to replace the xenon lamp assembly in an existing projector.

These considerations have long intrigued projector makers. The laser technology itself goes back more than a decade, when U.S. and German companies developed laser light sources to go into flight simulators for pilot training. IEEE Life Fellow Peter Moulton and I conceived the company Laser Light Engines to commercialize the laser system Moulton developed for the U.S. Air Force Research Laboratory. This system used infrared laser diodes to pump a laser crystal, which produced another infrared laser beam. That beam went into a series of nonlinear optical crystals that converted the infrared into the red, green, and blue beams. Nowadays, the company uses an aggregation of semiconductor laser diodes to produce the red and blue laser beams. The red beam is generated with gallium arsenide–based diodes, with quantum wells of aluminum gallium indium phosphide. The blue are gallium nitride diodes, with indium gallium nitride quantum wells. The green comes from a high-powered, frequency-doubled, diode-pumped laser.

Early on, though, it was far from clear that lasers were the way forward. Their biggest problem was a shimmery image artifact called speckle. Instead of a patch of solid color with completely uniform brightness, early laser projectors produced images with sparkling surfaces that seemed to dance and move, especially if you moved your head. Speckle occurs because the surface roughness of most movie screens is on the order of a wavelength of visible light. So rays of laser light reflecting from the screen constructively and destructively interfere with one another.

Thus laser projectors seemed dead on arrival until Laser Light Engines, which is based in Salem, N.H., solved the speckle problem in 2010. It developed several solutions before settling on one: broadening the spectral bandwidth of the red, green, and blue beams enough to avoid speckle. For that it uses a proprietary nonlinear optical process, which effectively reduces the coherence of the laser beam, widening the bandwidth of the colored beams from about 0.1 nanometers to 10 to 30 nm.

After speckle was tackled, the challenges became more conventional: delivering as many as 600 watts of total laser power while achieving the desired figures for projector lifetime, energy efficiency, and cost. These goals are 50 000 hours or about 10 years, 10 white lumens per wall-plug watt, and an acquisition cost lower than that of a lamp-based projector, plus the many bulbs needed over its lifetime (these lamps cost about $1000 apiece). Laser Light Engines is close to achieving all of these figures; the last goal will be the most difficult, but I am confident that it will be achieved in three to five years.

All the major projector makers have now joined Laser Light Engines in building laser-illumination systems. The brightest of these projectors can put out 70 000 lumens—several times as many as an arc-lamp projector. That brightness is more than enough to offset the losses caused by 3-D. This past November, Laser Light Engines and NEC demonstrated projectors with this new light source at the Technicolor facility in Burbank, Calif.

Higher brightness benefits not just 3-D but 2-D movies, too. The reason is that more brightness means a greater range of luminance, or brightness, from sunlight bright to deep black. But to take advantage of that wider range, software specialists will have to increase the number of levels of digital encoding between bright and dark pixels, to create a smooth ramp in brightness over that extended range. This increase in "bit depth" per pixel in turn will require huge increases in digital bandwidth, but it'll be worth it. Today, movies don't even come close to displaying the natural contrast that the human eye can see.

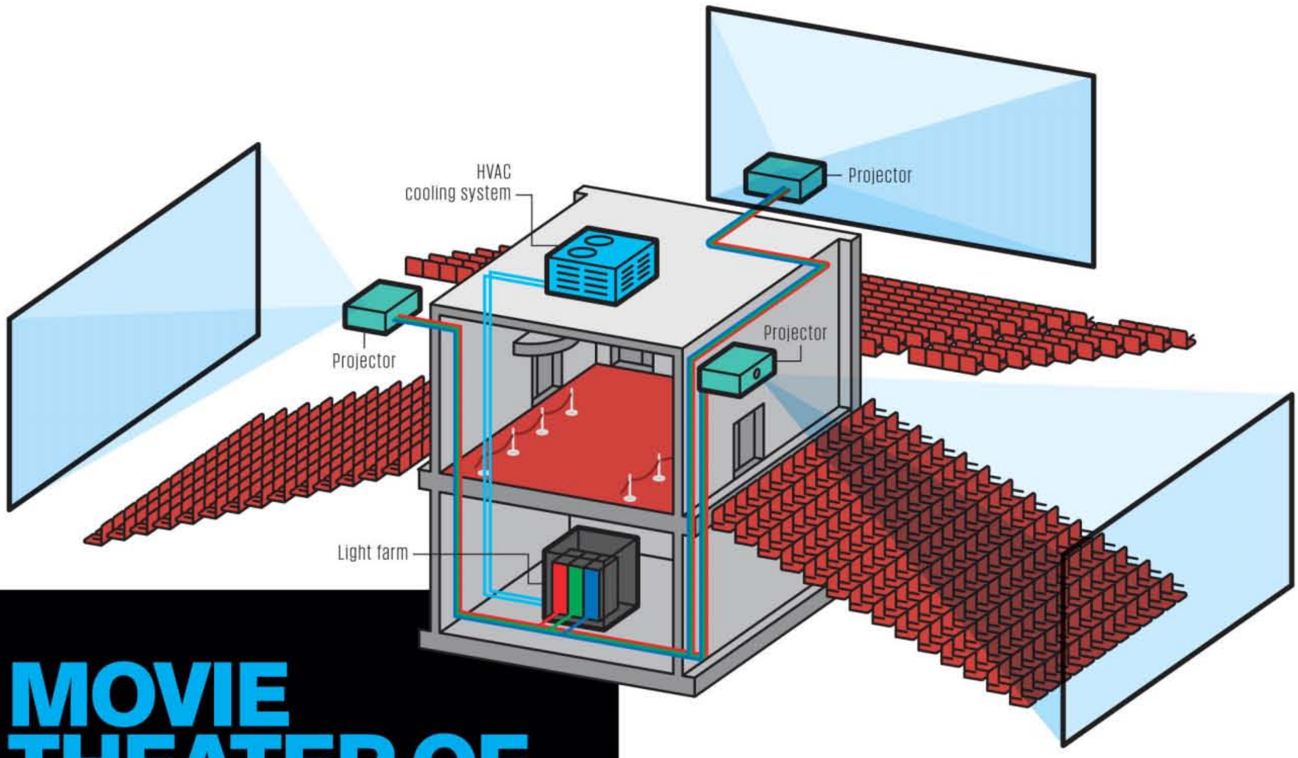
IN THE LONGER TERM, digital cinema and laser projectors will far transcend the boundaries of traditional film. Today's arc-lamp-based projectors can produce only about 40 percent of the colors that most people are capable of perceiving, whereas laser-based systems can reproduce up to around 60 percent. Laser illumination can also project much more saturated colors because its red, green, and blue beams can have much narrower spectral bandwidth than filtered lamp light.

This vastly greater, brighter, and more saturated palette will translate into movies that are more vivid than anything possible today. But such an advance won't come easily: More colors will require coordinated changes to global standards, and that won't happen without a *lot* of arguing over how "wide" to go. More colors will require more bits, which will in turn require more bandwidth to and within the projector.

Higher contrast and color rendering aren't the only factors that will increase the size of movie files. Movie directors are starting to use frame rates higher than 24 per second, the standard since around 1927. Peter Jackson's *The Hobbit: An Unexpected Journey* (2012) was filmed at 48 frames per second, as was its recent sequel, *The Hobbit: The Desolation of Smaug*. A movie's frame rate has a huge influence on how the viewer perceives motion, and it also increases perceived contrast and resolution. Higher frame rates allow the appearance of fast-moving objects to remain super-sharp and can eliminate the jerky effects that can arise when the camera or the subject is moving. But as with higher dynamic range, there is a price to pay. Showing more frames per second increases not only the quantity of data in the movie file but also the data-transmission rates necessary to project that movie.

Yet another possibility for future movies is greater spatial resolution, or pixels per scene. This resolution is limited by spatial-light-modulator technology, either DMD or LCoS. Most

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



MOVIE THEATER OF THE FUTURE

IN A MULTIPLEX THEATER, a single "light farm" with powerful lasers—red, green, and blue—will supply multiple movie-projector heads, one for each auditorium. The projector heads will be connected to the light farm by armored fiber-optic cables, one each for the red, green, and blue beams. The lasers in the light farm will be cooled by liquids circulated through a roof-mounted cooling system.

theaters today show movies in 2K (2 211 840 pixels per frame). Some motion-picture executives would like to see a migration to 4K (8 847 360 pixels per frame).

However, as resolution doubles, the uncompressed data required increases by a factor of 4. So, again, the refrain is "more bandwidth, please."

What does all this mean? If you were to make a 2-hour motion picture with an extended color range in 4K and at 48 frames per second, the raw (uncompressed) movie file would occupy more than 15 terabytes. For comparison, the total amount of data in all of the e-mails sent in the United States in one year has been estimated to be 10.6 TB.

All of these parameters–luminance (brightness), chrominance (color), frame rate, and even laser-pulse rate–will be independently adjustable on future movie projectors. This controllability will make the projector more versatile, enabling it to present many different levels of image quality. This processing, done on the fly in the projector, will ensure the highest image quality for a given data rate.

These developments will inevitably change movie theaters. Already, new "projector head" designs are available that contain no light source, only the spatial light modulators and the optics that create the moving image and focus it on the screen. Connected by a fiber-optic cable, these projector heads can be fed with laser light from sources that are tens of meters away. So it is likely that a future multiplex theater will have a centrally located "light farm" in which racks of high-power red, green, and blue lasers will be supported by efficient power supplies and liquid cooling from the cinema's rooftop HVAC system.

Compact projector heads would hang from the ceiling of each auditorium in the theater. Red, green, and blue laser light from the light farm would be channeled into separate armored, fiber-optic cables that snake through the walls of the theater to the projection heads in the auditoriums. With such a scheme, there would be no need for a projection booth in the theater. The projectors and light farm could be controlled from remote network operating centers, greatly reducing the overhead costs of running a chain of theaters.

All of these improvements will require more engineering and also big, complex, and coordinated system-level developments. There will have to be more compromises and consensus. And the payoff is never certain: Some observers contend that a generation has already been trained to be content with the small screen.

I say that there will always be a market for premium, large-format, truly social entertainment. But we'd better get on with it. Cinema must evolve if it's going to get us off the sofa and into the theater. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/projector0314

ILLUSTRATION BY James Provost

HOW DO YOU STORE A DIGITAL MOVIE FOR 100 YEARS?

THE MOTION-PICTURE INDUSTRY MUST FIND A WAY TO PRESERVE ALL-DIGITAL WORKS FOR FUTURE GENERATIONS

By ANDY MALTZ

THINK ABOUT YOUR FAVORITE MOVIE: Is it a classic, like *Citizen Kane*? Maybe it's something from the French New Wave, such as *Jules and Jim*. Or perhaps it's a contemporary blockbuster, like *Avatar*. Now imagine that movie just disappeared, and you could never watch it again on the big screen. • You don't need to worry about anything like that happening at the moment because the major movie studios go to great lengths to protect their treasures. They can do this efficiently and inexpensively for one reason: Photochemical film is cheap and easy to preserve. All you need is a cold room that's not too humid and not too dry, and the chemically processed film will last for 100 years or longer. Film archivists know that because many works from the earliest days of motion pictures, produced in the first decade of the 20th century or even before, are still around. Centuries from now, it'll be easy enough to retrieve what's stored on such films–a process that requires little more than a light source and a lens–even if information about how exactly those movies were made is lost.

Illustration by CHAD HAGEN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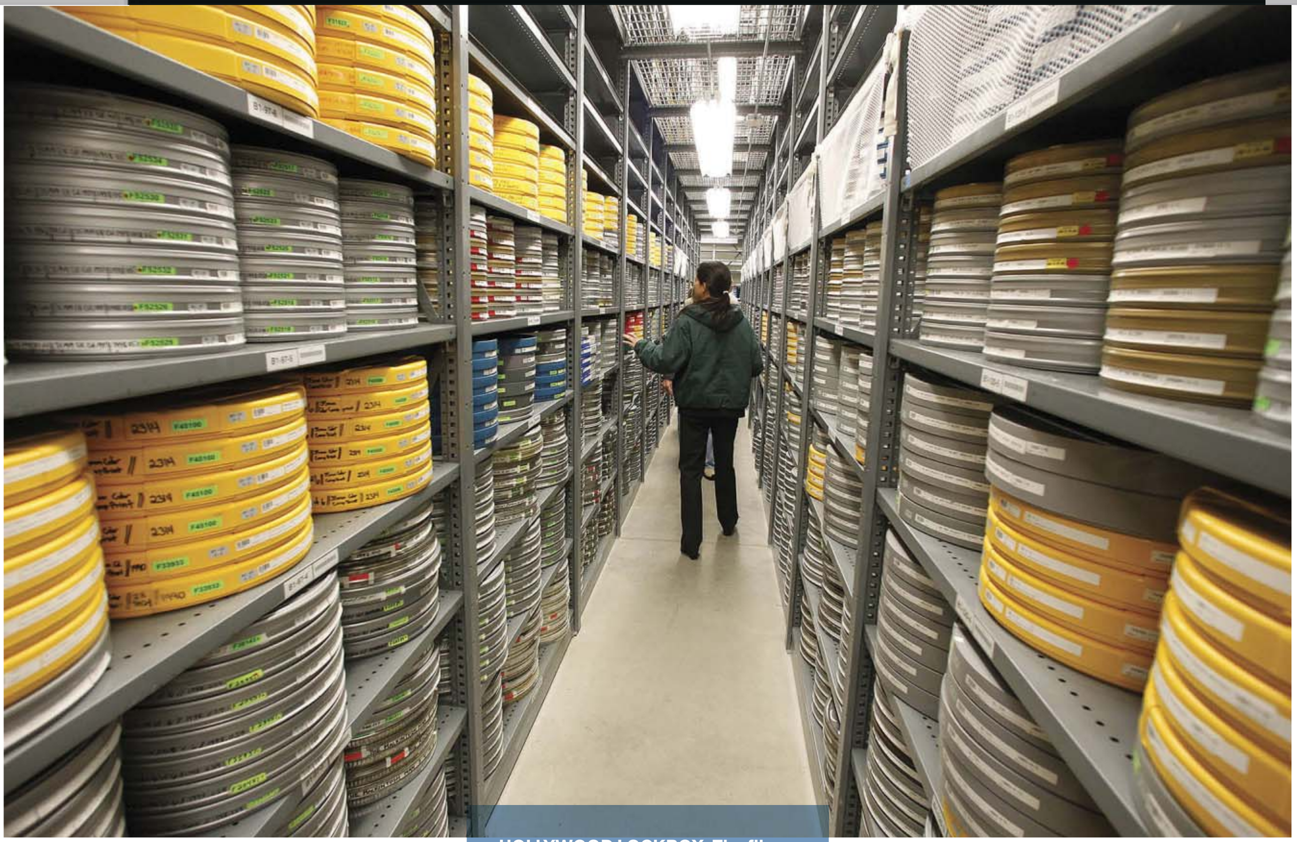
2a
3a



HOLLYWOOD LOCKBOX: The film archive at the Academy of Motion Picture Arts and Sciences has four climate-controlled vaults that house reels for 70 000 movies.

But times are changing: The advent of digital cinematography means that most movies these days are not shot on film but recorded as bits and bytes, using specialized electronic motion-picture cameras. The resolution and dynamic range of the digital images can be as good as or better than those captured on 35-millimeter film, so there's generally no loss of quality. Indeed, the changeover from film to digital offers many economic, environmental, and practical benefits. That's why more than 80 percent of movie theaters in the United States no longer handle film: They use digital projectors and digital playback systems exclusively. [For more on digital projection technology, see "Lasers Light Up the Silver Screen," in this issue.]

For the most part, this transition has been a boon to moviemakers and viewers alike. But as "born digital" productions proliferate, a huge new headache emerges: preservation. Digital movies are not nearly as easy to archive for the long term as good old film. In 2007, the Science and Technology Council of the Academy of Motion Picture Arts and Sciences estimated that the annual cost of preserving an 8.3-terabyte digital master is about US $12 000—more than 10 times what it costs to preserve a traditional film master. (This figure is based on an annual cost of $500 per terabyte for fully managed storage of three copies. While this cost has declined since the report was published, it remains significant.) And that doesn't include the expense of preserving alternate versions or source material for a movie or the ongoing costs of maintaining accessibility to the digital work, as file formats, hardware, and software change over time.

If you take pictures with a digital camera or record video on a smartphone or store files on a laptop, you face the same problem, albeit on a smaller scale. Every few years, you have to transfer all that digital content to the latest recording medium or risk losing it altogether. You might attempt to free yourself of that hassle by archiving your digital collections in the cloud, but keep in mind that no cloud service can be relied on to keep your data alive forever. When the photo-storage site Digital Railroad shut down abruptly in 2008, for instance, it gave users just 24 hours to download their images before pulling the plug. Some professional photographers and photo agencies lost years' worth of work.

Even though it generates petabytes of new digital footage each year, the motion-picture industry still has no better solution than you have to the looming problem of data extinction.

THE PHENOMENON OF DIGITAL MOVIES IS RECENT, but not exactly new. The Academy of Motion Picture Arts and Sciences (the group responsible for the Academy Awards) began paying serious attention to digital cinema technologies back in 2003, when it formed the Science and Technology Council (which I manage) and charged it with, among other things, monitoring technology developments in the film industry.

Even then, the writing was on the wall: Digital technologies would soon eclipse film as the dominant means of movie production, distribution, and projection. But what about preservation? In 2005, the academy sponsored a Digital Motion Picture Archiving Summit, which brought together specialists from the major Hollywood studios and U.S. film archives, including the U.S. Library of Congress, to discuss the long-term preservation of these digital works.

The summit in turn led to the academy's 2007 report, *The Digital Dilemma: Strategic Issues in Archiving and Accessing Digital Motion Picture Materials*, which looked at preservation issues

PREVIOUS PAGES: *TITANIC*: PICTORIAL PRESS/ALAMY; THIS PAGE: FRED PROUSER/REUTERS not just in the movie world but also in government, medicine, science, and the oil-and-gas industry. Not surprisingly, the report concluded that each of these enterprises faces similar issues with digital data, and nobody has yet come up with a good long-term solution. A follow-on report in 2012 examined digital archiving for independent filmmakers, documentarians, and nonprofit archivists, who are in even worse shape because they lack the financial wherewithal and organized infrastructure of the major studios.

This is not the first movie-preservation crisis. Before the industry switched to fire-resistant "safety film" in the 1950s, motion pictures were shot on highly flammable nitrate-based film, which generates its own oxygen while burning and is therefore nearly impossible to extinguish once ignited. Early movie producers didn't really care about archiving either. Stories abound of nitrate-film bonfires on studio lots because movies had no perceived long-term value to justify the cost of storing them. According to researchers at the Library of Congress, less than half of the feature films made in the United States before 1950 and less than 20 percent from the 1920s are still around. The early films that did survive did so largely through the efforts of private and institutional collectors.

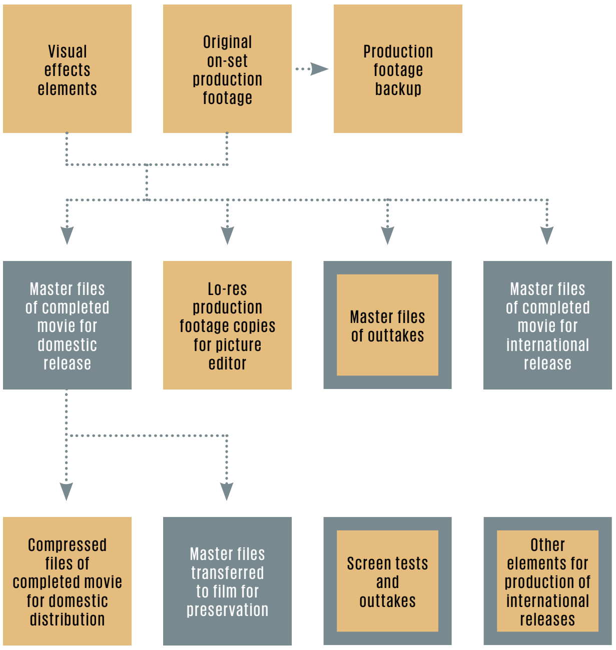
Attitudes changed with the introduction of home video–VHS and Betamax, followed by DVD, Blu-ray, and now Internet streaming–which gave movie studios a strong economic incentive to make their content last. Older material could be sold to new audiences every few years, and titles with a narrower appeal could remain profitable. And so the major Hollywood studios began investing heavily in archiving facilities, on their studio lots and in deep, underground temperature- and humidity-stable caverns throughout the United States. These days the studios tend to save everything, including various versions of finished movies, as well as the original camera negative film, original camera data (for digitally captured movies), original audio recordings, still photographs taken on set, notated scripts, and more.

As the days of analog film draw to a close, moviemakers and archivists now must confront a host of new issues. Most of them spring from the fact that the digital information stored in a master copy of a movie represents the movie only indirectly. Many layers–the storage medium, the hardware and software interfaces between that medium and the computer used, that computer's operating system and its file system, the digital image and sound file formats, the imaging and sound application software–all need to work in concert to turn the 0s and 1s into what we think of as a movie.

This complexity isn't a big deal over short time horizons, but for archival purposes–considered to be 100 years or longer for motion pictures and "the life of the Republic" for records deposited in the U.S. National Archives–it becomes a real concern. Most computer hardware is designed for a useful life of no more than three to five years, and most software–operating systems and applications alike–is superseded by upgraded versions every few years. Remember 8-inch and 5.25-inch floppy disks? There is still some legacy hardware and software around that can read them, but for practical purposes, those dinosaurs are extinct.

MAKING A MOVIE, STEP BY STEP

MOTION-PICTURE PRODUCTION has always required many different elements to create the film prints (and now digital files) that audiences see in domestic and international movie theaters. Shown here is a high-level view of these elements, color-coded according to longevity (yellow is for working files, gray for archived elements, and yellow with a gray border for working files that are also archived).



Also, digital storage requires active management. That is, the data must be checked regularly for errors, multiple copies must be maintained in different locations, technical staff must continually refresh their skills to keep abreast of new technologies and techniques, and the electricity bill always needs to be paid. Digital data, unlike film, cannot survive long periods of benign neglect.

The rapid obsolescence of digital technology has forced all of us who use it into a continual process of data migration–regularly copying data collections from old media and file formats to new. You can do that fairly easily when you replace your old laptop with a new one, but the process does not scale up well to collections measured in tera- or petabytes. Copying and reformatting masses of data that size quickly becomes impractical.

To give a crude example, just moving a petabyte of data (that's 1 billion megabytes) over a gigabit Ethernet connection takes upwards of 90 days. Now, a single feature-length digital motion picture generates upwards of 2 petabytes, the equivalent of almost half a million DVDs. And worldwide, about 7000 new feature films are released each year. So it's not hard to see why data migration alone isn't a long-term solution.

IF THIS SITUATION SOUNDS OMINOUS, IT IS. True, the cost per bit of digital storage has dropped dramatically over the last three decades: A gigabyte of storage 30 years ago might have run you a couple hundred thousand dollars; these days, it's mere pennies. And there's reason to believe that advances in automation will lower labor costs, while advances in energy efficiency will reduce power bills.

But once you're on the technology treadmill, it is impossible to get off. For large collections of important or valuable digital data—not just motion pictures but news footage, scientific measurements, governmental records, and our own personal collections—today's digital storage technologies simply do not work to ensure their survival for future generations. The uncertain state of digital preservation is such that most major studios continue to archive their movies by transferring them to separate, black-and-white polyester-based film negatives, one each for red, green, and blue. This is the case even for those works that are born digital.

Three years ago, Dominic Case of Australia's National Film and Sound Archive made the following observation, which still holds true: "Even if we could switch to a low-cost, low-maintenance, secure digital solution tomorrow, we'd still need our film collection to last for 100 years, because it would take that long to transfer everything onto it."

The good news is that there is a lot of work being done to raise awareness of the risk of digital decay generally and to try to reduce its occurrence. The Library of Congress, active in this area for many years, is leading these efforts through its National Digital Stewardship Alliance. The Data Conservancy, headquartered at Johns Hopkins University's Sheridan Libraries, is similarly working on solutions. And the National Academies' Board on Research Data and Information is studying digital curation as a future career opportunity. With these and other groups focused on digital preservation, the movie industry may well come up with some workable strategies—or at least be able to find people who can.

One promising thrust led by the motion-picture academy is the development of format standards for digital-image files, through its Academy Color Encoding System, or ACES. Work on ACES began 10 years ago, at a time when there was no clear standard for interchanging digitally mastered motion-picture elements. The Digital Picture Exchange or DPX file format (also known as the SMPTE 268M-2003 standard) was and still is widely used, but it leaves many technical details up to the end user, which leads to many different interpretations and implementations as well as a proliferation of proprietary and nonstandard formats. These days, the digital images moviemakers create can be recorded using any one of a dozen or more file formats and color-encoding schemes. The result of all that variety is reduced efficiency, increased costs, and degraded image quality, because everyone in the production chain has to play "guess the format."

ACES aims to eliminate the ambiguity of today's file formats. In simple terms, selected raw footage gets converted into the ACES format, which renders it clearly interpretable at any later step in the moviemaking process, including the addition of visual effects, postproduction, and mastering. And it yields a usable archival master in a digital form.

BORN DIGITAL: The 2011 feature *The Girl with the Dragon Tattoo* was produced entirely in digital format. But for archiving purposes, such digital works are transferred to color-separated, black-and-white negative film, because there's still no other way to preserve such all-digital works.

AF ARCHIVE/ALAMY

ACES is currently being used in many motion pictures, blockbusters and small films alike. It's also being adopted in television production, because it produces higher quality images than do HDTV standards. Equipment manufacturers and postproduction and visual-effects facilities are also adopting it and participating in the ongoing refinement of the system. And the Society of Motion Picture and Television Engineers has already published five ACES standards documents, with more on the way.

The academy has also mounted what we call the Digital Motion Picture Archive Framework Project. As part of that effort, we created in partnership with the Library of Congress an experimental system for managing a 20-terabyte digital movie, plus 76 TB of related material. Given that there were no commercial products for performing such a task, the project team adapted various pieces of open-source software. We called the resulting package ACeSS, for Academy Case Study System, which we continue to use and learn from. Among the things we discovered from that exercise is the crucial role of metadata for maintaining long-term access to digital materials. That is, the information that gets stored needs to include a description of its contents, its format, what hardware and software were used to create it, how it was encoded, and other detailed "data about the data." And digital data needs to be managed forever, so the organization and its preservation processes need to be built to last.

So what can you do to ensure your own important digital collections don't disappear? Follow the best practices for data curation: Store multiple copies in multiple locations, regularly check the health of your data, and keep your hardware, software, and file formats up to date. And if you're an engineer or computer scientist up for a grand challenge, investigate ways to make the problem of digital-information decay itself become obsolete. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/filmarchive0314

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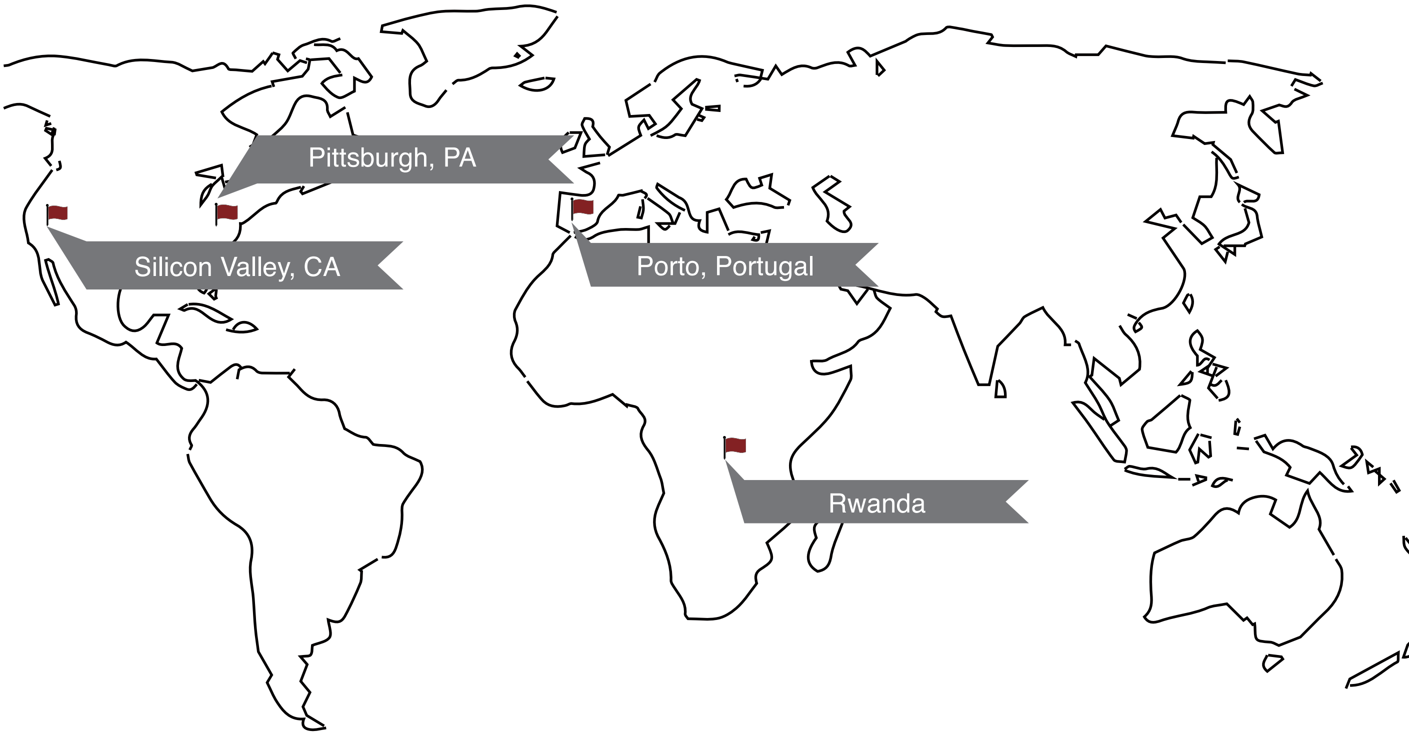

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IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

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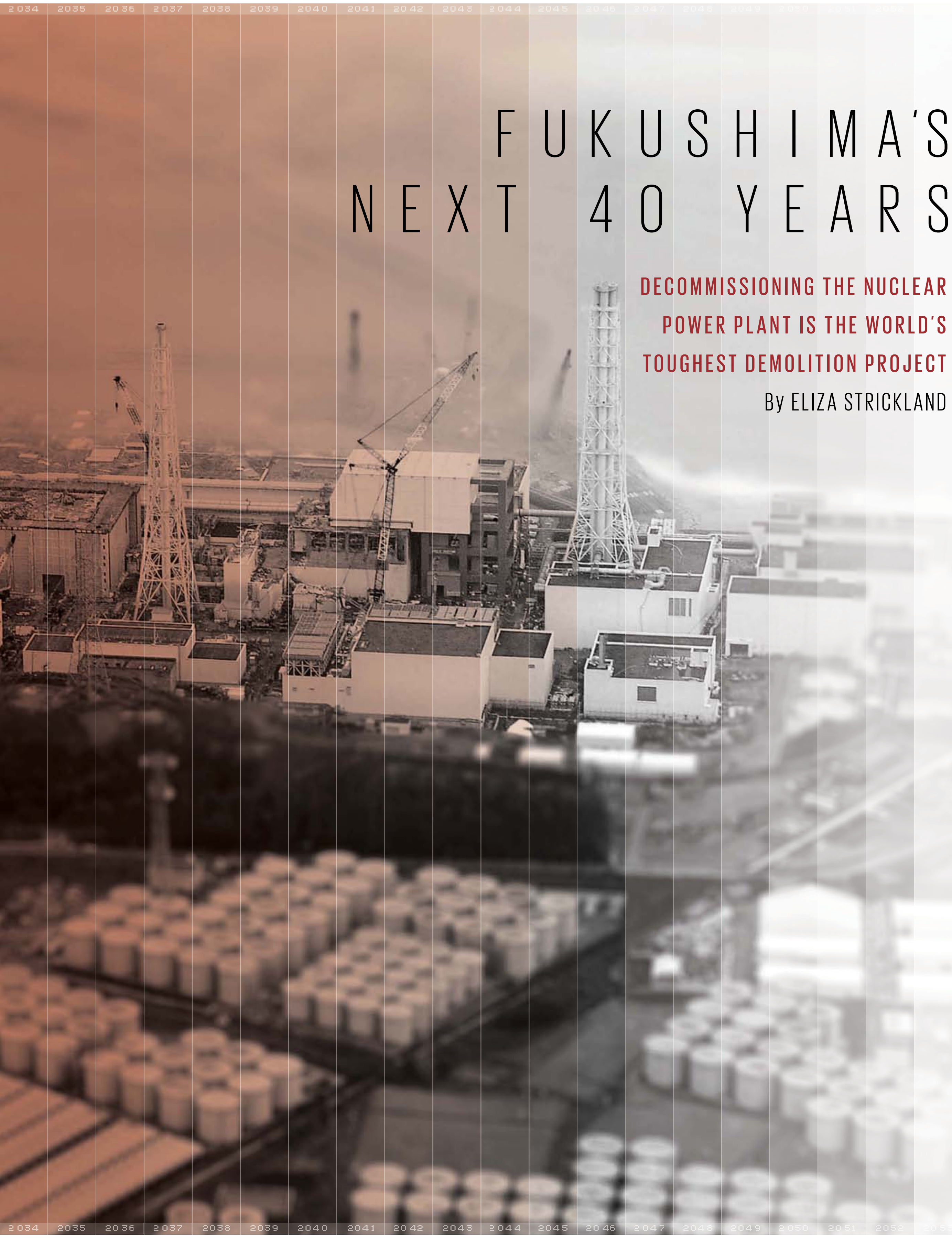


FUKUSHIMA'S NEXT 40 YEARS

DECOMMISSIONING THE NUCLEAR POWER PLANT IS THE WORLD'S TOUGHEST DEMOLITION PROJECT

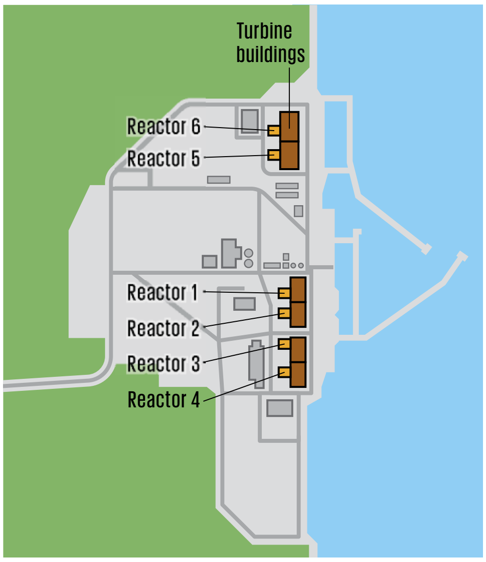
By ELIZA STRICKLAND

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

A radiation-proof superhero could make sense of Japan's Fukushima Daiichi nuclear power plant in an afternoon. Our champion would pick through the rubble to reactor 1, slosh through the pooled water inside the building, lift the massive steel dome of the protective containment vessel, and peek into the pressure vessel that holds the nuclear fuel. A dive to the bottom would reveal the debris of the meltdown: a hardened blob of metals with fat strands of radioactive goop dripping through holes in the pressure vessel to the floor of the containment vessel below. Then, with a clear understanding of the situation, the superhero could figure out how to clean up this mess.

Unfortunately, mere mortals can't get anywhere near that pressure vessel, and Japan's top nuclear experts thus have only the vaguest idea of where the melted fuel ended up in reactor 1. The operation floor at the top level of the building is too radioactive for human occupancy: The dose rate is 54 millisieverts per hour in some areas, a year's allowable dose for a cleanup worker. Yet, somehow, workers must take apart not just the radioactive wreck of reactor 1 but also the five other reactors at the ruined plant.

This decommissioning project is one of the biggest engineering challenges of our time: It will likely take 40 years to complete and cost US $15 billion. The operation will involve squadrons of advanced robots, the likes of which we have never seen.



THE SITE: During the 2011 accident, reactors 1, 2, and 3 suffered partial meltdowns. Explosions shattered reactor buildings 1, 3, and 4. Reactors 5 and 6 are undamaged.

Nothing has been the same in Japan since 11 March 2011, when one of history's worst tsunamis flooded Fukushima Daiichi, crippled its emergency power systems, and triggered a series of explosions and meltdowns that damaged four reactors. A plume of radioactive material drifted over northeast Japan and settled on towns, forests, and fields, while plant workers scrambled to pour water over the nuclear cores to prevent further radioactive releases. Nine months later, the Tokyo Electric Power Co. (TEPCO), the utility company that operates the plant, declared the situation stable.

Stability is a relative concept: Although conditions at Fukushima Daiichi aren't getting worse, the plant is an ongoing disaster scene. The damaged reactor cores continue to glow with infernal heat, so plant employees must keep spraying them with water to cool them and prevent another meltdown. But the pressure vessels and containment vessels are riddled with holes, and those leaks allow radioactive water to stream into basements. TEPCO is struggling to capture that water and to contain it by erecting endless storage tanks. The reactors are kept in check only by ceaseless vigilance.

TEPCO's job isn't just to deal with the immediate threat. To placate the furious Japanese public, the company must clean up the site and try to remove every trace of the facility from the landscape. The ruin is a constant reminder of technological and managerial failure on the grand scale, and it requires a proportionally grand gesture of repentance. TEPCO officials have admitted frankly that they don't yet know how to accomplish the tasks on their 40-year road map, a detailed plan for decommissioning the plant's six reactors. But they know one thing: Much of the work will be done by an army of advanced robots, which Japan's biggest technology companies are now rushing to invent and build.

Here's some more bad news: Chernobyl and Three Mile Island, the only other commercial-scale nuclear accidents, can't teach Japan much about how to clean up Fukushima Daiichi. The Chernobyl reactor wasn't dismantled; it was entombed in concrete. The Three Mile Island reactor was defueled, but Lake Barrett, who served as site director during that decommissioning process, says the magnitude of the challenge was different. At Three Mile Island the buildings were intact, and the one melted nuclear core remained inside its pressure vessel. "At Fukushima you have wrecked infrastructure, three melted cores, and you have some core on the floor, ex-vessel," Barrett says. Nothing like Fukushima, he declares, has ever happened before.

Barrett, who is now a consultant for the Fukushima cleanup, says TEPCO is taking the only approach that makes sense: "You work from the outside in," he says, dealing with all the peripheral problems in the buildings before tackling the heart of the matter, the melted nuclear cores. During the first three years of the cleanup, TEPCO has been surveying the site to create maps of radiation levels. The next step is removing radioactive debris and scrubbing radioactive materials off walls and floors. Spent fuel must be removed from the pools in the reactor buildings; leaks must be plugged. Only then will workers be able to flood the containment structures so that the melted globs of nuclear fuel can safely be broken up, transferred to casks, and carted away.

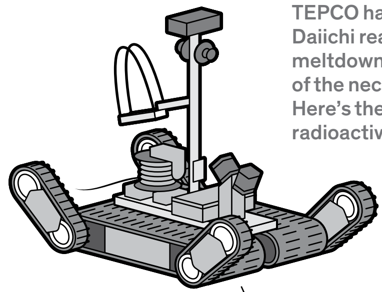
Many of the technologies necessary for the decommissioning already exist in some form, but they must be adapted to fit the unique circumstances of Fukushima Daiichi. "It's like in the 1960s, when we wanted to put a man on the moon," says Barrett. "We had rocketry, we had physics, but we had never put all the technologies together." Just as with the moon shot, there is no guarantee that this epic project can be accomplished. But faced with the wrath of the Japanese people, TEPCO has no choice but to try.

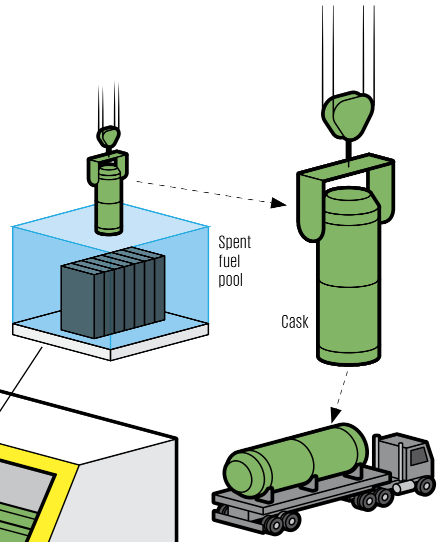
TO BEGIN THE FIRST STEP—inspection—TEPCO sent in robots to map the invisible hot spots throughout the smashed reactor buildings. The first to arrive were the U.S.-made PackBot and Warrior, hastily shipped over

ILLUSTRATIONS BY James Provost

HOW TO TAKE APART A MELTED-DOWN REACTOR

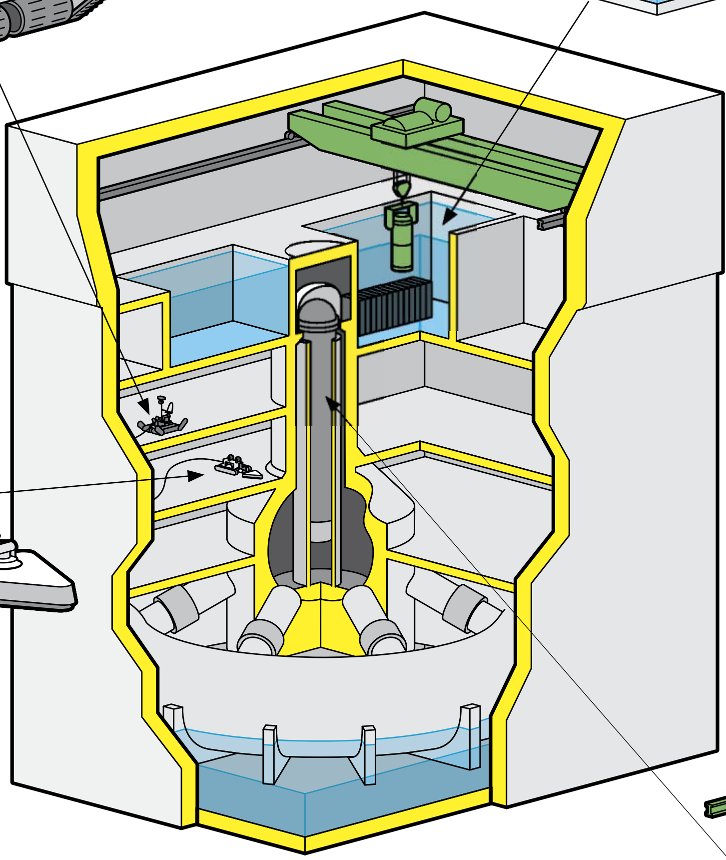
TEPCO has a rough plan for dismantling the Fukushima Daiichi reactors that experienced explosions and meltdowns, although the company admits that some of the necessary tools and robots don't exist yet. Here's the 40-year procedure for cleaning up a highly radioactive disaster scene, in five not-so-easy steps.





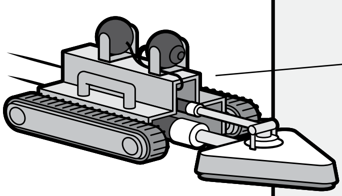
1. INSPECTION

First, map the reactor building's radioactive hot spots. Use robots with dosimeters and gamma ray detectors to determine radiation levels throughout the building.



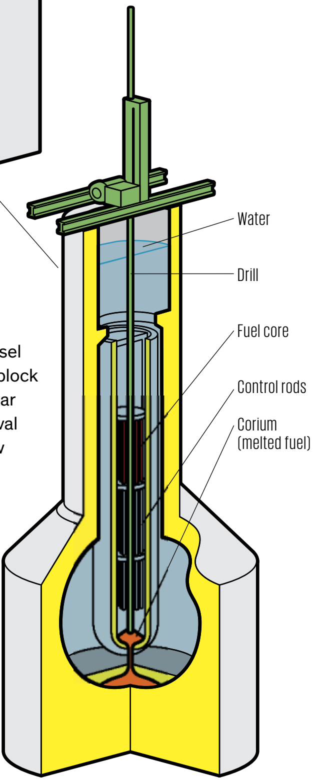
3. SPENT FUEL REMOVAL

To empty the spent fuel pool, lower a cask into the pool and pack it with fuel assemblies. Then transport the cask to a pool in a safer location and unpack its cargo. Repeat until the spent fuel pool is empty.



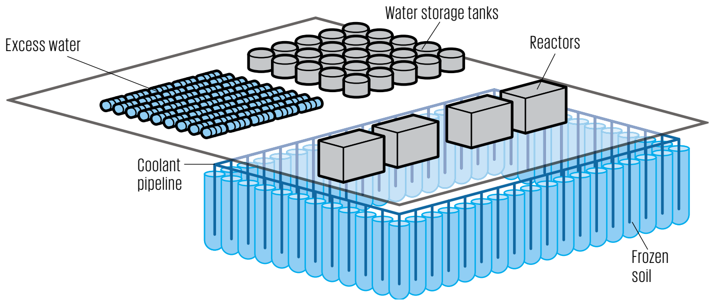
2. DECONTAMINATION

Next, send in scrubber bots to scour the walls and floors. The robots must bring down radiation levels so that humans can safely work inside the building and manage complex tasks.



4. CONTAINMENT OF RADIOACTIVE WATER

Every day, groundwater flowing through the site mixes with radioactive water leaking from the reactor buildings. For a short-term fix, install storage tanks to hold the ever-accumulating water. Then put an end to the problem by creating a subterranean wall of frozen soil that will divert the flowing groundwater away from the reactor buildings. Finally, plug up the leaks inside the reactors.



5. CORE REMOVAL

Fill the containment vessel to the top with water to block radiation from the nuclear core and make its removal feasible. Determine how much of the melted nuclear fuel is still inside the pressure vessel, and how much has leaked down to pool on the floor of the containment vessel below. Then drill down to break the melted fuel into chunks, pack those chunks into a cask, and cart it away. You're done.

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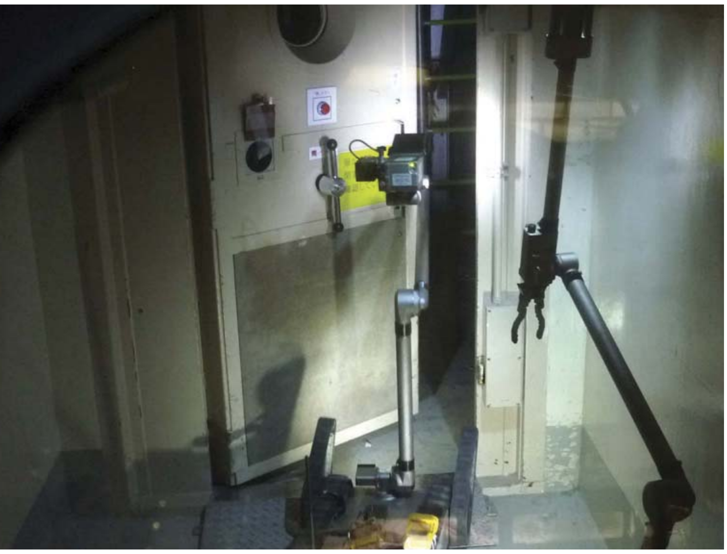
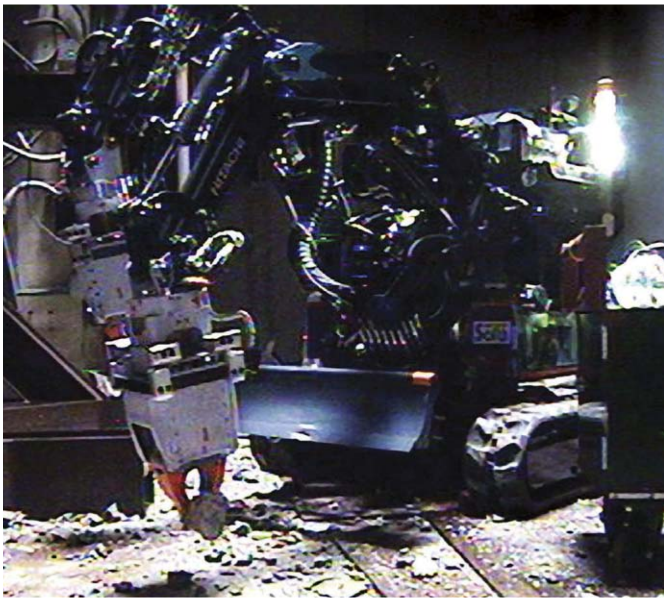
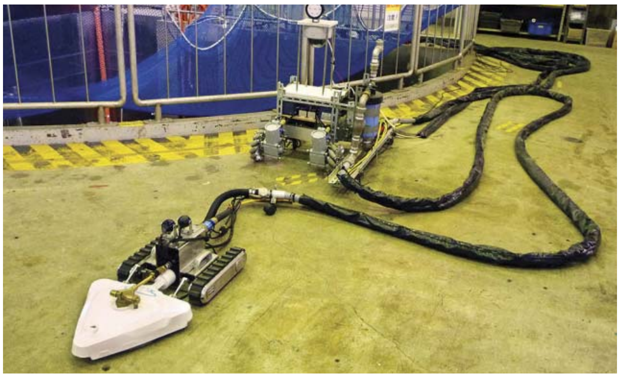
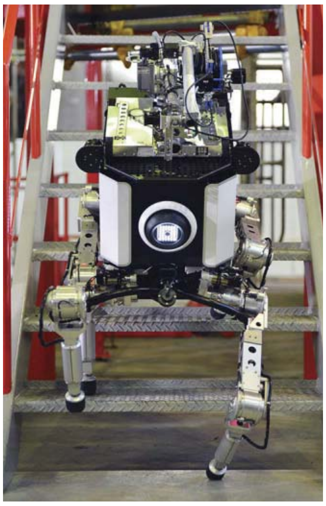








ROBOT LABORERS: Inside the Fukushima Daiichi reactor buildings, iRobot's PackBot inspects [top left], Hitachi's ASTACO-SoRa picks up debris [top right], and Atox Co.'s Raccoon [bottom left] scrubs radioactive surfaces clean. This tetrapod [bottom middle] from Toshiba and the Quince [bottom right] from Chiba Institute of Technology are both inspector bots.

from iRobot Corp. of Bedford, Mass. But Japan is justly proud of its own robotics industry, so the question arose, Why didn't TEPCO have robots ready to respond in a nuclear emergency? Yoshihiko Nakamura, a University of Tokyo robotics professor, has the dispiriting answer. The government did fund a program on robotics for nuclear facilities in 2000, following a deadly accident at a uranium reprocessing facility. But that project was shut down after a year. "[The government] said this technology is immature, and it is not applicable for the nuclear systems, and the nuclear systems are already 100 percent safe," Nakamura explains. "They didn't want to admit that the technology should be prepared in case of accident."

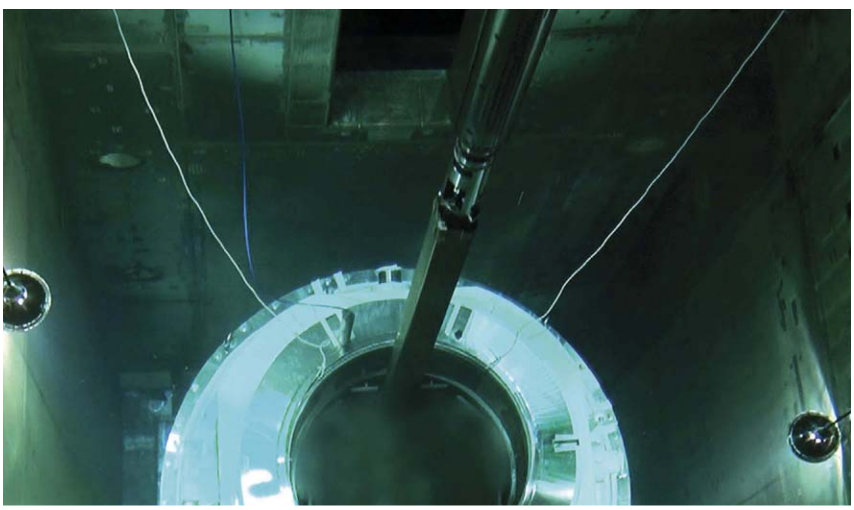
Still, some roboticists in Japan carried on their own research despite the government's indifference. In the lab of Tomoaki Yoshida, a roboticist at the Chiba Institute of Technology, near Tokyo, robots have learned to crawl over rubble and to climb up and down steps. These small tanks roll on a flexible series of treads, which can be lifted or lowered individually to allow the bot to manage stairs.

After the Fukushima accident, Yoshida's academic research became very relevant. With seed money from the government, he constructed two narrow metal staircases proportioned like the 5-floor staircases inside the Fukushima Daiichi reactor buildings. This allowed Yoshida to determine whether his bots could navigate those cramped stairs and tight turns. His acrobatic Quince robots proved themselves able, and after hundreds of tests they received TEPCO's clearance for field operations. In the summer of 2011, the Quince bots became the first Japanese robots to survey the reactor buildings.

The Quinces were equipped with cameras and dosimeters to identify radioactive hot spots. But the robots struggled with a communication issue: The nuclear plant's massive steel and concrete structures interfere with wireless communication, so the Quinces had to unspool cables behind them to receive commands and transmit data to their operators. The drawback of that approach soon became apparent. One Quince's cable got tangled and damaged on the third floor of reactor 2, and the lonely bot is still sitting there to this day, waiting for commands that can't reach it.

Back at Yoshida's lab, where modest bunk beds bespeak the dedication of his students, the team is currently working on a new and

CLOCKWISE FROM BOTTOM LEFT: TEPCO (3); THE YOMIURI SHIMBUN/AP PHOTO; YOSHIKAZU TSUNO/AFP/GETTY IMAGES



OUT OF THE POOL: Spent fuel pools inside the damaged reactor buildings contain hundreds of nuclear fuel assemblies, some of which are covered with debris [above] from the accident's explosions. TEPCO is emptying reactor 4's pool [top left] first. In the extraction process, a cask is lowered into the pool and filled with radioactive fuel assemblies. Then the cask is transported to a safer location, lowered into another pool [bottom left], and unloaded. It will take 70 trips to empty the reactor 4 pool.

TEPCO (3)

improved survey bot named Sakura. To guard against future tangles, Sakura not only unspools cable behind, it also automatically takes up the slack when it changes direction. It's waterproof enough to roll through puddles, and it can carry a heavy camera capable of detecting gamma radiation. The bot can tolerate that radiation: Yoshida's team tested its electronics (the CPU, microcontrollers, and sensors) and found that they're radiation-tolerant enough to perform about 100 missions before any component is likely to fail. However, the robot itself becomes too radioactive for workers to handle. Sakura must therefore take care of itself: It recharges its batteries by rolling up to a socket and plugging itself in.

The second step in the Fukushima decommissioning is decontamination, because only when that is complete will workers be able to get inside to tackle more complex tasks. The explosions that shattered several of the reactor structures sprayed radioactive materials throughout the buildings, and the best protective suits for workers in hot zones are of little use against the resulting gamma radiation–a worker would have to be covered from head to toe in lead as thick as the width of a hand.

After the accident, the Japanese government called for robots that could work on decontamination, and several of Japan's leading companies rose to the challenge. Toshiba and Hitachi have designed robots that use jets of high-pressure water and dry ice to abrade the surfaces of walls and floors; the robots will scour away radioactive materials along with top layers of paint or concrete and vacuum up the resulting sludge. But the robots' range is defined by their own communication cables, and they can carry only limited amounts of their cleaning agents. Another bot, the Raccoon, has already begun nosing across the floor in reactor building 2, trailing long hoses behind it to supply water and suction.

To clear a path for the robotic janitors, another class of robots has been invented to pick up debris and cut through obstacles. The ASTACO-SoRa, from Hitachi, has two arms that can reach 2.5 meters and lift 150 kilograms each. The tools on the ends of the arms–grippers, cutting blades, and a drill–can be exchanged to suit the task. However, Hitachi's versatile bot is limited to work on the first floor, as it can't climb stairs.

Removing spent fuel rods is the third step. Each reactor building holds hundreds of spent fuel assemblies in a pool on its top floor. These unshielded pools, perfectly safe when filled with water, became a focus of public fear during the Fukushima Daiichi accident. After reactor building 4 exploded on 15 March, many experts worried that the blast had damaged the structural integrity of that building's pool and allowed the water to drain out.

Selling Nuclear Safety to the Public

Lights go out during the Fukushima Daini drill.

In a mock-up control room at the Fukushima Daini plant, 10 kilometers down the coast from Fukushima Daiichi, workers in blue tracksuits man their stations, monitoring the screens and dials that display the operating parameters of a nuclear reactor. Then a thunderous roar booms through the room, and a shout goes up: "Earthquake!" The workers brace themselves and hold on to metal rails—but the room is not actually shaking. It's just a safety drill. TEPCO routinely conducts these training sessions, varying the disaster scenarios to ensure that its workers are ready for any kind of malfunction or natural catastrophe.

These drills are part of a campaign by Japan's big utilities to convince the government and the public that the country's nuclear reactors should be reopened, and that they should get back to the business of providing electricity. Before the Fukushima Daiichi crisis, 54 reactors provided about 30 percent of the country's electric power. Right now, not a single reactor is in operation. Utility companies are importing fossil fuels to make up the shortfall, but that work-around is taking an economic toll on the companies and their customers alike.

Japan's current administration supports reopening some nuclear plants, and in 2012 the government established a new oversight agency, the Nuclear Regulation Authority, to set stricter safety standards. The NRA has declared that no reactor built over an active seismic fault can reopen, and it has already targeted one reactor for closure on that basis. The agency also set new requirements for defenses against earthquakes, tsunamis, and power outages, and the utility companies are scrambling to bring their facilities up to code.

At TEPCO's Kashiwazaki-Kariwa plant, the world's largest nuclear power station, workers are erecting a 15-meter-high wall between the buildings and the sea to guard against future tsunamis. Each of the plant's seven reactors has three emergency diesel generators to power its cooling systems, but if all of those fail the plant can now rely on gas turbines aboard trucks stationed on a hill 35 meters above sea level; these turbines can provide power to the reactors for two days. A new water reservoir, 45 meters above sea level, can provide all the cooling water the plant would need for one week.

But even if TEPCO builds a wall up to the sky and installs a miniature ocean on the hilltop, the Kashiwazaki-Kariwa plant still might not reopen: The local government hasn't yet given its approval, and many residents are opposed to the restart. Throughout the country, people express considerable unease about a return to nuclear power. In a recent newspaper poll, nearly 60 percent of respondents said they don't agree with the government's pro-nuclear policies.

Back at Fukushima Daini, where workers diligently conduct their safety drills, TEPCO has made some upgrades to its buildings and emergency power systems. But Noriyuki Imaizumi, deputy superintendent of the power station, says there is no official plan to restart the plant and that the prefectural government is against it. Imaizumi says the deciding vote will ultimately come from the people of the towns near Fukushima Daini—towns that are still evacuated due to radioactive contamination.

"I feel we have to get the residents' approval if we are to restart," Imaizumi says. For now, Fukushima Daini's workers will come to work each day on a company bus that drives down empty roads and through empty towns. They'll conduct their drills and keep vigil over the plant's four reactors, making sure they're safe and stable—and that they can be restarted should conditions allow. "The residents will return eventually," Imaizumi says, "and when they do, we have to show ourselves ready to do whatever they decide." —E.S.

The pool was soon determined to be full of water, but not before the chairman of the U.S. Nuclear Regulatory Commission had caused an international panic by declaring it dry and dangerous. The reactor 4 pool became one of TEPCO's urgent decommissioning priorities, not only because it's a real vulnerability but also because it's a potent reminder of the accident's terrifying first days.

The process of emptying that pool began in November 2013. TEPCO workers use a newly installed cranelike machine to lower a cask into the pool, then long mechanical arms pack the submerged container with fuel assemblies. The transport cask, fortified with shielding to block the nuclear fuel's radiation, is lowered to a truck and brought to a common pool in a more intact building. The building 4 pool contains 1533 fuel assemblies, and moving them all to safety is expected to take a year. The same procedure must be performed at the highly radioactive reactors 1, 2, and 3 and the undamaged (and less challenging) reactors 5 and 6.

Containing the radioactive water that flows freely through the site is the fourth step. Every day, about 400 metric tons of groundwater streams into the basements of Fukushima Daiichi's broken buildings, where it mixes with radioactive cooling water from the leaky reactor vessels. TEPCO treats that water to remove most of its radioactive elements, but it can't be rendered entirely pure–and as a result local fishermen have protested plans to release it into the sea. To store the accumulating water, TEPCO has installed more than 1000 massive tanks, which themselves must be monitored vigilantly for leaks.

TEPCO hopes to stop the flow of groundwater with a series of pumps and underground walls, including an "ice wall" made of frozen soil. Still, at some point the Japanese public must grapple with a difficult question: Can the stored water ever be released into the sea? Barrett, the former site director of Three Mile Island, has argued publicly that the processed water is safe, as contamination is limited to trace amounts of tritium, a radioactive isotope of hydrogen. Tritium is less dangerous than other radioactive materials because it passes quickly through the body; after it's diluted in the Pacific, Barrett says, it would pose a negligible threat. "But releasing that water is an emotional issue, and it would be a public relations disaster," he says. The alternative is to follow the Three Mile Island example and gradually dispose of the water through evaporation, a process that would take many years.

TEPCO must also plug the holes in the reactor vessels that allow radioactive cooling water to flow out. Many of the leaks are thought to be in the suppression chambers, doughnut-shaped structures that ring the containment vessel and typically hold water, which is used to regulate temperature and pressure inside the pressure vessel during normal operations. Shunichi Suzuki, TEPCO's general manager of R&D for the Fukushima Daiichi decommissioning, explains that one of his priorities is developing technologies to find the leak points in the suppression chambers.

"There are some ideas for a submersible robot," Suzuki says, "but it will be very difficult for them to find the location of the leaks." He

ELIZA STRICKLAND

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

WATER, WATER EVERYWHERE: Groundwater flowing through the site mixes with radioactive cooling water leaking from reactor buildings and must therefore be stored and treated. To contain the accumulating water, TEPCO is filling fields with storage tanks [above]. These tanks must be monitored for leaks [left]. In August 2013, TEPCO admitted that 300 metric tons of contaminated water had leaked from one tank.

LEFT: TEPCO; RIGHT: THE YOMIURI SHIMBUN/AP PHOTO

notes that both the suppression chambers and the rooms that surround them are now filled with water, so there's no easy way to spot the ruptures; it's not like finding the hole in a leaky pipe that's spraying water into the air. Among the robot designs submitted by Hitachi, Mitsubishi, and Toshiba is one bot that would crawl through the turbid water and use an ultrasonic sensor to find the breaches in the suppression chambers' walls.

If robots prove impractical, TEPCO may take a more heavy-handed approach and start pouring concrete into the suppression chamber or the pipes that lead to it. "If it's possible to make a seal between the containment vessel and the suppression chamber, then the leaks don't matter," Suzuki says. One way or another, TEPCO hopes to have all the leaks stopped up within three years. Sealing the leaks is a necessary precondition for the final and most daunting task.

REMOVING THE THREE DAMAGED nuclear cores is the last big step in the decommissioning. As long as that melted fuel glows inside reactors 1, 2, and 3, Fukushima Daiichi will remain Japan's ongoing nightmare. Only once the fuel is safely packed up and carted away can the memory begin to fade. But it will be no easy task: TEPCO estimates that removing the three melted cores will take 20 years or more.

First, workers will flood the containment vessels to the top so that the water will shield the radioactive fuel. Then submersible robots will map the slumped fuel assemblies within the pressure vessels; these bots may be created by adapting those used by the petroleum industry to inspect deep-sea oil wells. Next, enormously long drills will go into action. They must be capable of reaching 25 meters down to the bottoms of the pressure vessels and breaking up the metal pooled there. Other machines will lift the debris into radiation-shielded transport casks to be taken away.

Making the task more complicated is the design of the reactors. They have control rods that project through the bottom of the pressure vessels, and the entry point for each of those control rods is a weak spot. Experts believe that most of the fuel in reactor 1, and some in reactors 2 and 3, leaked down through those shafts to pool on the floor of the containment vessel below. To reach that fuel, some 35 meters down, TEPCO workers will have to drill through the steel of the pressure vessel and work around a forest of wires and pipes.

Before TEPCO can even develop the proper fuel-handling tools, Suzuki says, the company must get a better understanding of the properties of the corium—the technical term for the mess of metals left behind after a meltdown. The company can't just copy the drills that broke up the melted core of the Three Mile Island reactor, says Suzuki. "At Three Mile Island, [the core] remained in the pressure vessel," he says. "In our case, it goes through the pressure vessel, so it melted stainless steel. So our fuel debris must be harder." The melted fuel may also have a lavalike consistency, with a hard crust on top but softer materials inside. TEPCO is now working with computer models and is planning to make an actual batch of corium in a laboratory to study its properties.

When the core material is broken up and contained, it will be whisked away to some to-be-determined storage facility. Over the decades its radioactivity will gradually fade, along with the Japanese public's memory of the accident. It's a shame that those twisted blobs of corium are too dangerous to be displayed in a museum, where a placard could explain that we human beings are so clever, we're capable of building machines we can't control.

Depending on whom you ask, nuclear power stations like Fukushima Daiichi are exemplars of either humanity's ingenuity or hubris. But, the museum placard might add, these metallic blobs, plucked from the heart of an industrial horror, prove something else—that we humans also have the grit and perseverance to clean up our mistakes. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/fukushima0314

OPEN-SOURCE DRONES FOR FUN AND PROFIT

FRIDAY IS FLY DAY at 3D Robotics, a maker of small robotic aircraft. So here we are, on a windswept, grassy landfill with a spectacular view of San Francisco's Golden Gate Bridge, looking up at a six-prop copter with a gleaming metal frame. It's like a spiffy toy from the future. Buzzing like a swarm of bees, it lifts off smartly, hovers, then pinwheels.

"Jason's making the hex twirl," says CEO Chris Anderson, a trim man in jeans and an untucked oxford shirt. "That's just for show–a human pilot couldn't do that." That's because Jason, the flight tester, did nothing more than figuratively push a button. The hexarotor–technically, the 3DR Y-6–is on autopilot, which it demonstrates by zooming off on a preprogrammed route. The Y-6 sells for US $619. That's a lot for a toy, but it's chicken feed for a capital investment.

These mini unmanned aerial vehicles, a.k.a. UAVs, a.k.a. drones–are changing from toys into tools, as businesses worldwide awaken to their importance.

FLY, MY PRETTIES: Chris Anderson [center] and his merry band of dronemasters test multicopters near San Francisco Bay.

Start-up 3D Robotics dreams of dominating the skies

BY PHILIP E. ROSS
PHOTOGRAPHY BY CHRIS MUELLER

It's happening fast: Twenty thousand of these inanimate insects will be skittering through U.S. skies by decade's end, according to the Federal Aviation Administration. That's provided the FAA soon issues regulations for their commercial use, a job it was supposed to have completed long ago.

"At first, investors thought drones were not a market," Anderson says. "Then, around nine months ago, they realized they were one. Now the question is, will we be the leader?"

In late September, just the day before this Fly Day, in fact, Anderson's company got $30 million from venture capitalists. That second round of funding came on top of $6 million raised a year earlier and will help 3D Robotics gear up for the commercial market that the FAA is preparing to allow.

And while his company bulks up, Anderson hopes that its roots in the amateur, DIY community will keep it close enough to the market to let it fend off the big boys—companies like FedEx, Germany's DHL delivery service, Domino's Pizza, and Amazon. All have recently chosen to talk up their own drone projects.

In November, Amazon's CEO, Jeff Bezos, got one of the biggest free advertisements in high-tech history by telling a television reporter that his company was working on copters to deliver small packages to customers' doorsteps. Bezos's scheme was basically preposterous, but that interview, and the accompanying video clip showing a pre-enactment of such a delivery, reverberated wildly. Which was, of course, the point.

Just a month earlier, Anderson had told *IEEE Spectrum* that using drones to deliver pizza was so much pie in the sky. "Anything that involves flying over people is going to be difficult," he said. "It's more than just the FAA here; it's a question of privacy."

Now, though, he diplomatically declines to beat up on tech honchos with blue-sky visions. "Bezos and others articulate a vision in the hope of encouraging it to happen," he says. "They're doing a proof of concept to show that the technology lies in reach, that it's worth considering. Worth beginning the regulatory discourse."

Anderson's flair for talking the talk of business shows how far he's come from his days as editor of *Wired* magazine. His self-reinvention began in the aughts, when he built a drone with his kids for fun. In 2007 he turned his new hobby into a Web-based community called DIYdrones.com. Then, in 2009, he cofounded 3D Robotics, helping it grow until at last he had to choose between it and his day job. Now he's the former editor of *Wired*.

If he speaks more frankly than other UAV entrepreneurs, though, it's only partly a vestige of his newshound roots. At least as important is his business model, which relies on both open-source hardware and software and thus laughs at secrecy. 3D Robotics patents nothing; it collaborates on everything, mainly through the DIY-drones community.

In 2011, when a graduate student in China translated a manual for a 3D Robotics UAV to help people who bought a Chinese version of the machine, Anderson says he was "angry—at first. But then I realized it was helping us. Our policy of open software and open hardware almost welcomes copycats." So he put a link to the translation on his site.

This approach is new, Anderson says. "Open hardware, drones, and the future of robotics; merging the [hobbyist] community and the company. If we get it right, it'll be a fantastic model for companies of all sorts; if we get it wrong, an instructive failure."

Hobbyists show off solutions to their own problems and get others to suggest improvements. Such helpers get to bask in the glow of 3D Robotics at an annual shindig in Colorado. Those who offer particularly valuable help get a 3D Robotics mug. A fortunate few—very few—actually get hired.

The poster child for that elite is Jordi Muñoz. He broke off his studies in electrical engineering in Mexico to spend two years on drone technology, cranking out C++ code for a UAV autopilot based on the Arduino microcontroller. Anderson heard of the autopilot, ordered a test version, and began an online dialogue that ended with the two men's founding of 3D Robotics. (The name refers to the one dimension where robots had not previously gone: up.)

"He mentored me on business, finance, legal, and P.R. matters," says Muñoz, now 26. "He also sent me some money." Muñoz moved the short (yet very long) distance from Tijuana, Mexico, to San Diego, Calif., to build the company's R&D office. Anderson stayed in Berkeley, Calif. When demand got big enough, they started up a factory in Tijuana; it recently added a second shift. Soon it may add a third.

Anderson won't give actual sales figures, but on another day, in San Diego, Muñoz lets a few numbers slip. The biggest seller is the autopilot circuit board: "Three hundred units a month; our ready-to-fly is at about 3000 a year," Muñoz says. Not bad for a business with a lot of upside.

What Anderson will say is that 3D Robotics has doubled its sales every year and should keep on doing so, and that it is now second in size only to DJI Innovations, in Shenzeng, China. That company's Phantom quadcopter competes directly against 3D Robotics' Iris. "It's not autonomous," Anderson sniffs. "It hovers, but it can't follow way stations," as Iris does.

Following way stations is what you'd want to do to survey the corners of, say, a farmer's field.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page
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2

HEADS UP: An engineer flies a quadcopter high over the 3D Robotics factory in Tijuana [1], which bustles with new, high-tech manufacturing. "Mexico is the new China," observes Chris Anderson [2], seen here outside the company's office in Berkeley, Calif. Not far away, on a landfill near San Francisco Bay [3], a flight tester launches a model under consideration as the company's fixed-wing platform. Also in Berkeley, a particularly muscular "hex" copter struts its stuff [4]. Some design work can be done onscreen [5]. Company cofounder Jordi Muñoz [6] plays with a quad indoors. Kids, don't try this at home.

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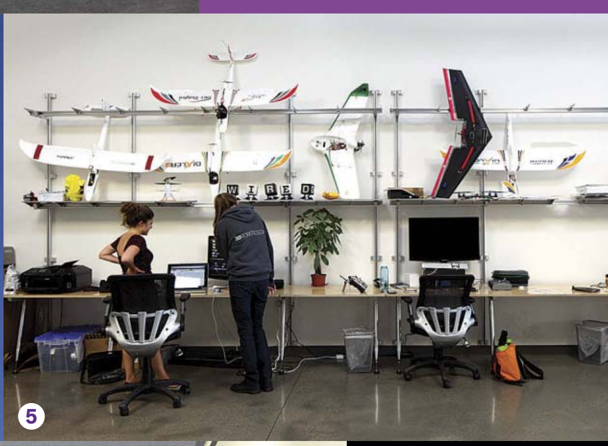

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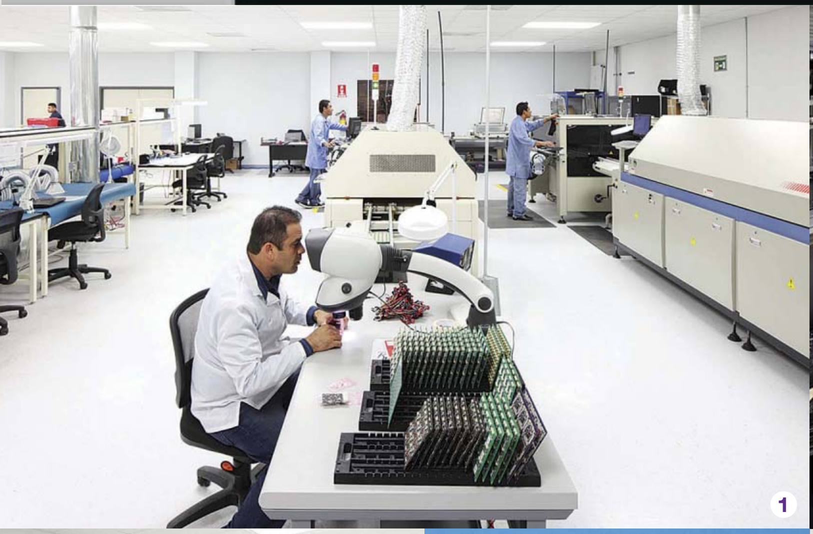

SOME ASSEMBLY REQUIRED: Employment at the Tijuana factory rises almost daily. Workers need watchmaker hands [1] and good old-fashioned tools [2]. The more routine assembly is done by pick-and-place machines [3]. One of the products is an autopilot, 3D Robotics' first big hit [4]. The company sells both components and ready-to-fly drones, which it configures to each customer's particular specifications [5].

And yes, agriculture is the first big business that Anderson expects to open up. There are already thousands of UAVs zooming around in military applications, of course. But Anderson isn't after that market. "Our developers are doing it for civilian use, and they've spoken loud and clear: They don't want their code to be weaponized," he says. Plus, selling to the military brings an array of often surreal challenges, he points out.

So, agriculture. Farms are far from the city's madding crowds and so offer safe flying areas; also, the trend toward precision agriculture demands aerial monitoring of crops. Like traffic watching, it's a job tailor-made for a robot: dull, dirty, and dangerous.

Ben Gielow, the general counsel for the Association for Unmanned Vehicle Systems International (AUVSI), figures that of the early commercial adopters "80 percent will be in agriculture, 10 percent in public safety, and 10 percent is everything else–mapping, say, or wildlife conservation." (Another of Anderson's targets is Hollywood, which uses copters for unorthodox camera angles.)

Farming apps for drones also have the advantage of already being legal, or at least it would seem so. When *Spectrum* asked the FAA's lawyers to comment, they replied: "Farmers may operate an unmanned aircraft over their own property for personal use and should operate safely so as to minimize risk to other aircraft or people or property on the ground." And they should be sure to wear sunscreen, too.

"I use it to manage our vineyards," says Ryan Kunde, a fifth-generation winemaker in Sebastapol, Calif., who uses a fixed-wing UAV fitted with one of 3D Robotics' Arduino autopilots. "We gather imagery from a bird's-eye view to see the variability and to change farming practices to reduce that variability." He says he has a company in the works that will sell aerial-monitoring services to other farmers as soon as the FAA says it can.

Farmers are also prime customers because they need a lot of customization–a key element in 3D Robotics' business model. Quadcopters, which are highly maneuverable, are needed if trees present obstacles to straightaway flight, Kunde says. Infrared cameras come in handy at "bud break" time, in the spring. "You'll have areas that 'push' earlier than others," he says. "If you could image that in a heat map of the vineyard, it would be cool to see the variation."

Anderson emphasizes customization to play up his community's edge in crowd-sourced solutions to problems. He sells several different rotorcraft and a fixed-wing plane, but he refers to them all as platforms. "You need a platform to be truly disruptive," Anderson says. "We're the Android of UAVs."

Take the gimbal, a camera-stabilizing device that typically has three degrees of freedom. Type in the keyword "gimbal" on the DIYDrone.com message board and you'll bring up thousands of comments, many including videos. Fiddling with these gizmos is a community effort, though often mediated by 3D Robotics' staffers.

Most of the company's copters are quads or hexes, which can carry up to twice as many propellers as they have arms by mounting counter-rotating pairs. Coaxial props provide useful redundancy; extra arms (as in the hex) provide greater stability. A doubled-up Y-6 known as the Beast has 12 motors and props. It can easily lift 2 kilograms. "Unfortunately, it's not for sale, because there's not much demand," says Justin Cunningham, a flight-test engineer in the San Diego office.

Problem is, these copters can stay up for only 10 minutes or so, 20 at most. That's okay for gentlemen farmers with tiny spreads, but others would opt instead for the company's fixed-wing platform, the 3DR ATF APM:Plane. Stripped down, it sells for $570, though as with the rotorcraft, the customer can pile on avionics, multiple radio receivers and antennas, cameras, and on and on.

On Fly Day, the dozen-odd staffers in Berkeley are auditioning a possible successor to the plane. They call it the Dark Knight, because it's as black as Batman's cape. Jason holds it at the end of a straining bungee cord and then lets go, slinging the plane straight into a brisk bay breeze. The plane rises to about 20 meters and flies at 15 knots, "maybe 30, with the wind," says Jason. But the plane struggles to gain and keep altitude; the lithium-polymer battery's a little spent.

If the truth be told, these batteries are anemic even when they're fully charged. Energy storage remains the industry bugbear. You can solve that problem by going big and ditching batteries for internal combustion engines. For 27 years, Japanese farmers have dusted their crops with Yamaha's RMAX robotic helicopter, a table-size robot with a two-stroke engine that lets it stay aloft for hours. "Japan's aviation authority didn't regulate it; their department of agriculture promoted it," says AUVSI's Gielow.

Another engine-powered drone, Boeing's ScanEagle, embarked last summer on the first FAA-approved commercial mission beyond the line of sight of its operator, ConocoPhilips. The reason for the approval? The plane flew over Arctic waters, looking for icebergs, whales, and other potential visitors to offshore drilling platforms. A crash, presumably, would bother nobody but the fishes.

Larger craft may not fare well under the FAA's rule, at least not anytime soon. As pilots say, when something goes wrong, it can ruin your whole day. In September, a New York City man was killed by his own Trex 700N, a 3-kilogram helicopter powered by an internal-combustion engine. Even small copters can be dangerous if they put all their power into just a single large blade.

3D Robotics multicopters' smaller blades are far more innocuous, and its fixed-wing plane carries its prop in the back, so it can't give anybody anything worse than a nasty bump. What's more, all its platforms run on electricity.

But that leaves the question of how to keep them up longer—and it's a big one, says Muñoz. There are many possibilities, he says, and all are on the table. You could minimize friction with a slower-spinning motor. Or you could supplement batteries with little fuel cells, "methanol—1 volt, which means 12 cells, but really, really small ones. Or you could even use a wire tether," he says.

Another challenge is quality control. As aviation regulators prepare for the industry's breakout to commercial users, even minor defects will have to end. At the 3D Robotics factory in Tijuana, East Asian quality-control protocols are being worked out, including scanner-readable tags on every item.

Guillermo Romero, the general manager, points out a fenced-in area that has been set aside to test every single ready-to-fly UAV before it gets shipped. Most defects, he says, are cosmetic, but even major problems are usually easy to repair. "We are moving from a 70 percent yield [before testing] to 80 percent; our goal is 97 percent," he says. The next step is to track every item with machine-readable tags.

Manufacturing began in a corner of Romero's Tijuana apartment, moved to a nearby space of 250 square meters, and moved again in the middle of 2013 to the present 1100-square-meter building. Assembly was mostly by hand; now it's mostly by machine.

To make GPS modules, for instance, an array of circuit boards goes in a pick-and-place machine called a Manncorp MC386. In parallel movements that handle several boards, suction devices pick an element—a resister, say—off a paper reel, put it where it's supposed to go, then perform another such operation. When all the slots are full, the boards go in an oven that heats them in a time-varying pattern that ensures that the different solders, on the different elements, melt at once and uniformly.

Romero holds up a matchbox-like autopilot. "Here's an ArduPilotMega, Jordi's thing," he says. "It's why we are all here."

That autopilot's packed with goodies. "Gyroscopes, accelerometers, a compass—you need that too, because you're not always moving!" Muñoz says. And he and his band of researchers are working on add-on hardware to make UAVs more aware of their surroundings. "You can always add more—a laser sensor's superaccurate, helps you avoid obstacles."

Avoiding obstacles, known in the trade as sense-and-avoid capability, is what UAVs need to achieve. Until then, they're shackled by safety regulations that require line-of-sight operation far from schools, pets, and angry birds. Obstacle avoidance is harder than you'd probably guess from those Internet videos showing UAVS zipping through slots in a wall and performing other acrobatic feats (as *Spectrum*'s Evan Ackerman calls it).

Those videos were taken in labs, with objects placed just where the UAV expects them to be, with robust full-motion tracking managed by external sensors and superfast wireless networks. Even very large drones have only recently managed to do anything like that in the wild.

Then again, only recently have we gotten used to walking around with smartphones in our pockets. And, as Anderson emphasizes, the smartphone is exactly the right analogy, more so than even the Pentagon's Predator drones. It was the smartphone market that spawned affordable GPS, fast local networking, and instant video, capabilities that today's mini UAVs depend on. When a UAV commercial market emerges, it too will plant the seeds of many other industries.

"What moves the needle is when hundreds of thousands use drones every day, for buzzing over crops or taking pictures of action sports," Anderson says. "The vast majority of amateurs do it because it pushes their emotional and intellectual buttons. Employees do what I tell them to; volunteers do what they want." ■

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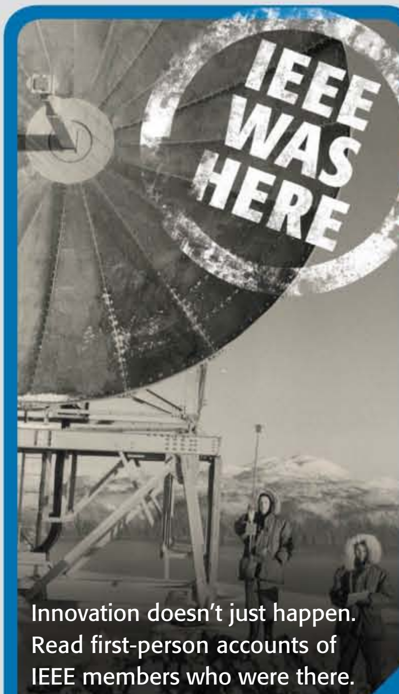
Applications:

Submit (in English) *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 March 31st, 2014 (until positions are filled). *For more information, visit http://www.shanghaitech.edu.cn.*



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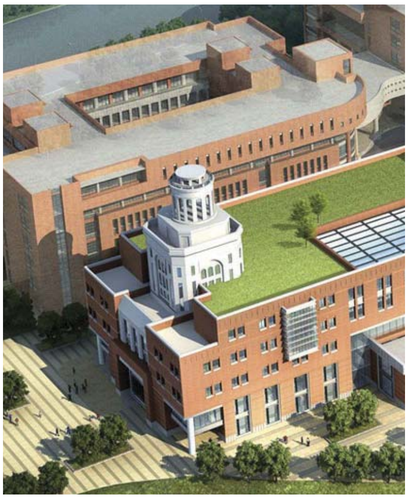

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Carnegie Mellon University

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NAZARBAYEV UNIVERSITY

ASTANA, KAZAKHSTAN

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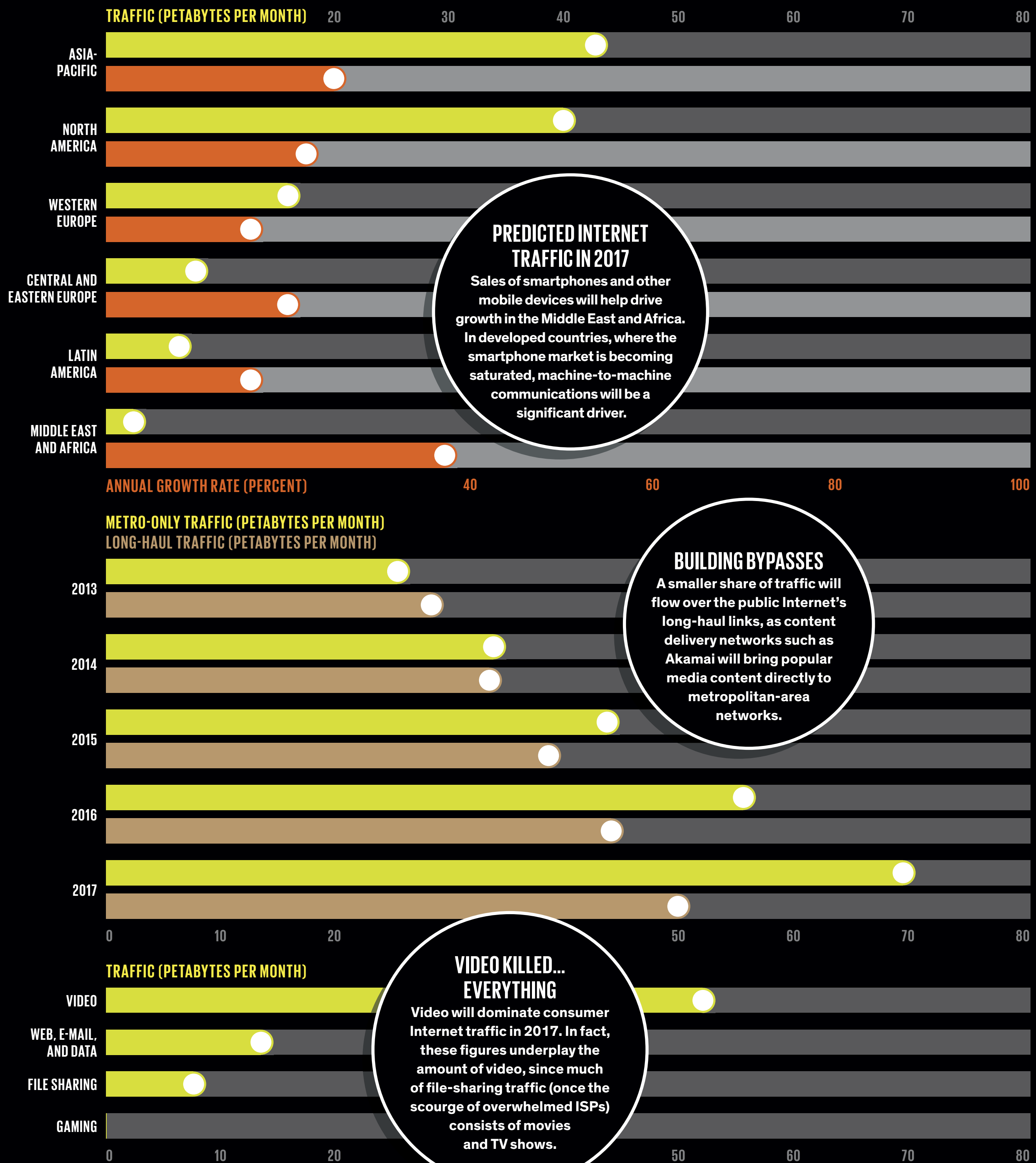
THE AGE OF THE ZETTABYTE

CISCO: THE FUTURE OF INTERNET TRAFFIC IS VIDEO

Based on observations made at ISPs around the world, Cisco forecasts that by 2017, annual global Internet traffic will rise to 1.4 zettabytes (that's 10^{21} bytes), compared to "just" 528 exabytes (10^{18} bytes) in 2012. At this time 80 to 90 percent of all consumer Internet traffic will be some form of video, but other sources contributing to the rise include machine-to-machine communication and the proliferation of mobile devices. —STEPHEN CASS



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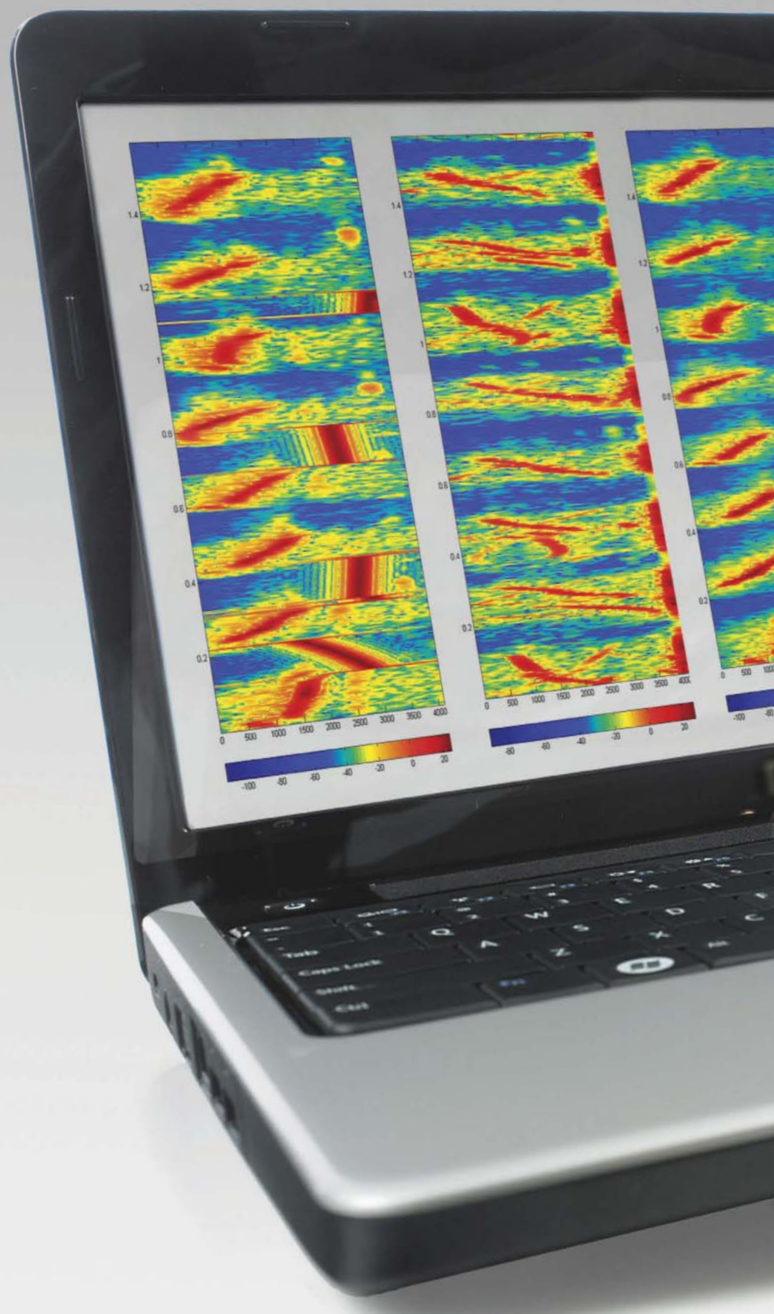

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