MIT Technology Review

VOL. 120 NO. 2 MARCH/APRIL 2017

10 Breakthrough Technologies

PLUS:

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The Politics of Robots and Jobs

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Virtual Reality Is the Art Form of the Future


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From the Editor

GUIDO VITTI

Every year, *MIT Technology Review* selects the 10 technologies we believe are the big breakthroughs of the last year: innovations that are a clear advance in their field.

We've published a list of the year's most impactful technologies since 2002. We're sometimes wrong. We once thought social media and broadcast television would merge (see "Social TV," May/June 2010). But they remain separate streams that people can experience simultaneously, tweeting their impressions of presidential debates as they watch them on TV. More often, we're not so much wrong as too early: cancer genomics, where doctors sequence the mutations of a patient's tumor to better match the drugs most likely to help, was less practicable when sequencing was more expensive (see "Cancer Genomics," May/June 2011).

What do we like? We are cross-disciplinary in our thinking: we enjoy tracing how developments in one field lead to advances in another. A breakthrough in artificial intelligence (see "Deep Learning," May/June 2013) has become crucial to the ambitions for self-driving cars (see "Tesla Autopilot," March/April 2016). We applaud ambitious solutions, such as Google's plan to bring Internet access to everyone in the world (see "Project Loon," March/April 2015). And we admire elegance and power: we were blown away when scientists used CRISPR to engineer two macaque monkeys, demonstrating the vast potential of gene editing (see "Genome Editing," May/June 2014).

This year's 10 Breakthrough Technologies reflect the same tastes. "Reinforcement Learning" (see page 32) describes an ambitious approach in AI: computers repeat an action until something difficult goes more smoothly, whereupon the system favors the behavior that led to that outcome. According to senior editor Will Knight, reinforcement learning is an old idea, toyed with by AI pioneers like Marvin Minsky, that never quite worked. But in March 2016, "AlphaGo, a program trained using reinforcement learning, destroyed one of the best Go players of all time … The feat was astonishing, because it is virtually impossible to build a good Go-playing program … Not only is the game extremely complex, but even accomplished players may struggle to say why certain moves are good or bad." Knight says that reinforcement learning, currently being explored by Uber, OpenAI, and DeepMind, could speed the development of self-driving cars and robots that can reliably grasp objects.

Or consider the cross-disciplinary approach in "Reversing Paralysis" (see page 82), which combines neuroscience and electronics. Senior editor Antonio Regalado describes how a French neuroscientist named Grégoire Courtine installed a recording device inside the skull of a semi-paralyzed macaque monkey, and then sutured electrodes around the animal's partially severed spinal cord. "A wireless connection joined the two electronic devices. The result: a system that read the monkey's intention to move and then transmitted it immediately in the form of bursts of electrical stimulation to its spine." Suddenly, the monkey's leg could extend and flex, and it "hobbled forward." In the past, a few people have controlled robotic arms using brain implants; but by wirelessly connecting brain-reading technologies to electrical stimulators, researchers like Courtine are creating "neural bypasses" that could allow the disabled to walk.

These are just two of the technologies in this year's list. Read all 10 technologies, and tell me which you think are most remarkable at jason.pontin@technologyreview.com.

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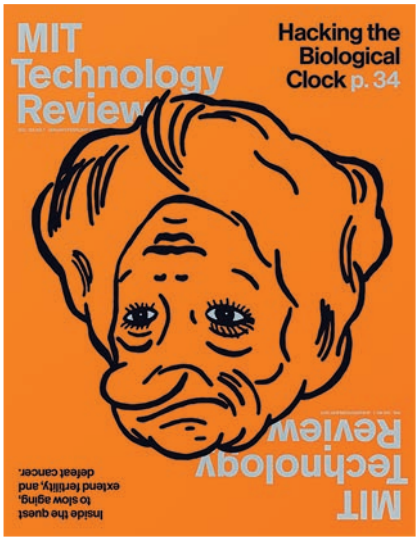
Letters and Comments

MIT Technology Review
Volume 120, Number 1



Cancer Sequencing Isn't Perfect, but Standard Care Is Worse

Steve Hall's otherwise well-balanced article ("The Cancer Lottery," January/February 2017) contained one misleading notion—that a patient must be at a major academic center to undergo genomic sequencing. In fact, genomic testing, often exceeding what's possible in university laboratories, is readily commercially available. Unfortunately, oncologists who order genomic sequencing often do so after other "standard" therapies have failed and no other treatment options remain—more or less at the end of life. This strategy is the least likely one to succeed, because the tumor burden may already be overwhelming, and the number of molecular aberrations in the cancer too vast and varied to be overcome by simple targeting strategies. The far better strategy is early diagnosis, when patients may have a relatively uncomplicated tumor genome.

But there are disincentives to this approach. Insurance companies don't cover molecular diagnostics, forcing otherwise willing doctors into unwelcome financial discussions with their patients. I also suspect most community oncologists don't bother to seek a molecular diagnosis because they simply don't have the resources available to deal with results that may be unfamiliar to them or point to treatments that require substantial work to access. In a world where time is money and no one pays for concierge levels of service, why bother? Some oncologists take on this burden nobly, for reasons other than money—but they're quite a rare breed.

In my practice, a small percentage of patients derive meaningful benefits from molecular diagnosis. But however unsatisfactorily low the number is, the alternative—standard care—is even worse. I for one can't imagine putting my head in the sand and going back to practicing as if everyone has the same disease. There may be growing pains, but the pre-molecular era of oncology hardly deserves any sentimentality. And what we're powerless to act on today may become a breakthrough news event in the near future.

Genomic sequencing is far from a panacea—knowing the truth about what's driving people's cancer doesn't always mean you can save them. But molecular diagnosis does mean survival for thousands of patients who would otherwise face an immediate death. This alone has forever changed the practice of oncology.

Michael P. Castro is a medical oncologist in Los Angeles.

I for one can't imagine putting my head in the sand and going back to practicing as if everyone has the same disease.

AI Can't Help Us, Because Online Trolls Aren't the Real Problem

The fundamental problem with online discourse ("If Only AI Could Save Us from Ourselves," January/February 2017) is that we've become less civil as a society. Online postings are a manifestation of that, but they're not the root of what's wrong. Political discourse over the past few cycles has disinhibited people from expressing their darkest sentiments. It's become okay to endorse ideas that people weren't openly admitting to several years ago.

Now that Trump's president, people who may have been sheepish about their views have had them validated. So they become even more willing to openly voice ideas once considered unacceptable.

We're not likely to see a meaningful decline in abusive postings anytime soon. Real live moderators will continue to be the most effective remedy, even as the volume of objectionable material they have to deal with expands.

Robert DeVellis lives in Chapel Hill, North Carolina.

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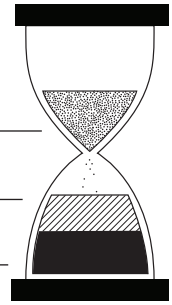
Twitter Votes

Reactions to our stories on AI and trolls, the digital divide, and Calico Labs.

Google's Calico Labs wants to extend the human life span. How long would you want to live for?

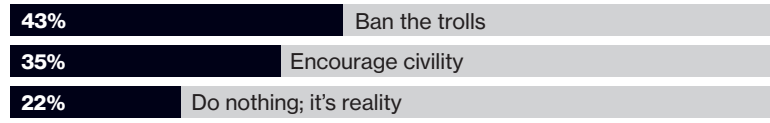


29% Forever

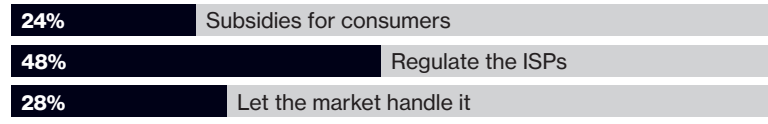
33% 150 years

36% Life's long enough now

How do you think abuse in online communities should be tamed?



What's the best way to close the digital divide?



Views

James P. Hoffa

Emma Brunskill

Kenneth Rogoff

ROBOTICS

Drivers Wanted

Self-driving trucks are an experiment, and we're the guinea pigs.

Imagine driving down the interstate past an 80,000-pound tractor-trailer. Its driver's hands aren't touching the wheel.

Tech companies envision—and are investing in—a future in which thousands of such vehicles would navigate our roadways (see "10 Breakthrough Technologies: Self-Driving Trucks," page 62). Most people don't welcome this scenario, nor should they. A 2016 study conducted by researchers at the University of Michigan Transportation Research Institute found that 95 percent of U.S. motorists had concerns about sharing the road with autonomous trucks and trailers. Safety was the major worry.

Skilled, experienced drivers play a huge role in ensuring the safe operation of heavy vehicles. The value of a human in that truck won't go away no matter what technology is developed.

Those who advocate for self-driving cars often cite the fact that human error is largely responsible for most traffic deaths. But that doesn't mean self-driving cars and trucks will be able to avoid those errors. An automated vehicle in Pittsburgh recently drove the wrong way up a one-way road. Last year in Florida a man using Tesla's Autopilot feature was killed when the system failed to recognize a tractor-trailer in front of the car. These are not doomsday scenarios; these are legitimate concerns.

There are other worries: with cybersecurity breaches now a frequent topic in the news, what happens when not just one but a "platoon" of trucks is hacked? The risks to the public only increase as more vehicle systems are controlled by computer. Don't forget that some of those trucks carry thousands of pounds of hazardous materials every day.

We don't yet have any federal regulations regarding automated vehicles. The government has issued guidelines for testing them, but they're voluntary guidelines for manufacturers, not regulations. A number of states allow testing for automated vehicles, but they all employ different standards.

Self-driving cars and trucks are an experiment. But our highways shouldn't be experimental grounds where public safety is put at risk. Yes, we should strive to innovate and make progress, but we also need to ensure that changes are indeed advancements for the betterment of our society—including the driving public and our nation's workers.

Anything man-made can fail. If that failure occurred in a heavy vehicle driving next to you, wouldn't you want a driver behind the wheel?

James P. Hoffa is the general president of the International Brotherhood of Teamsters.

ARTIFICIAL INTELLIGENCE

Playtime's Over

Getting computers to beat humans at games is impressive. But now the real work begins.

Early last year, a computer achieved world-class performance in the game Go—years before most people believed such a feat would be possible.

That's impressive, but our ambitions should be set higher. Computer science could help provide what the world critically needs: tools that enable all of us to reach beyond what we thought we were capable of. Reinforcement learning—an integral part of the Go success—can accelerate that process (see "10 Breakthrough Technologies: Reinforcement Learning," page 32).

ANDY FRIEDMAN

Reinforcement learning is a way of making a computer learn through experience to make a series of decisions that yield positive outcomes—even without any prior knowledge of how its actions will affect its immediate environment. A software-based tutor, for example, would alter its activities in response to how students perform on tests after using it.

If we hope to create artificial teaching agents using reinforcement learning, we'll need algorithms that are "data smart." We might gather data from online educational systems and use it to help the agent estimate the effectiveness of different teaching approaches. When a student logs in, should the system provide him with a problem to solve? Or would starting with an explanatory video be better? The data can help it decide.

But in some cases there's not enough data, or not the right kind of data, which makes it challenging to develop systems that make good decisions. It would be nice if we could create a system that didn't need so much data in the first place. And that's exactly what my group is working on—we're developing reinforcement-learning algorithms and statistical techniques to allow computers to develop good suggestions while using less data. We still have a lot of work to do, but we're tightening the gap between theory and practice.

In the end, we shouldn't leave it all to the computers. So-called "human-in-the-loop" reinforcement learning can accelerate the process, allowing algorithms to "reason" about their own limited performance and reach out to humans for help when they need, for example, to expand the set of possible decisions. My group and our collaborators at the University of Washington are now testing algorithms for a tutoring system that can tell if its current curriculum isn't enabling all students to learn well, and then asks people to add new hints to the system. Such human-computer collaborations could help students to learn using approaches we can't yet imagine. This vision of reinforcement learning has artificially intelligent agents redefining what outstanding human performance looks like—and enabling all of us to achieve it.

Emma Brunskill is an assistant professor of computer science at Stanford University.

CURRENCY

Paper Problem

Cash is passé. But digital money makes you easier to track.

One great challenge facing society is where to draw the line between an individual's right to privacy and the government's right to tax, regulate, and enforce the law. Few areas illustrate this problem as well as the way we spend our money.

Our transactions are increasingly digital (and thus easily tracked), and in places like China many companies are adopting biometrics (like fingerprints or eye scans) to verify who we are (see "10 Breakthrough Technologies: Paying with Your Face," page 72). In India, the government has taken biometric data from 1.1 billion people. But these developments alone don't give us a good answer to the question of what we should do with good old-fashioned paper currency.

There are 34 $100 bills floating around for every man, woman, and child in the country. A huge amount of that cash is being used to facilitate corruption and tax evasion.

The demand for cash has dwindled in the legal, tax-compliant economy, but the underground economy uses it as much as ever. Incredibly, given that 95 percent of Americans report that they've never held a $100 bill (the rest say they hold one occasionally), there are 34 $100 bills floating around for every man, woman, and child in the country. Similar figures hold for big bills in other advanced economies. What are they being used for? The evidence seems clear: a huge amount of the world's cash supply is used to facilitate tax evasion, crime, and corruption.

Given that, going to a completely cashless society might appear to be a great idea. But it's not so simple. Ordinary people rely on cash to protect their privacy, and cash still comes in handy during prolonged power outages. One way to deal with the problem might be to phase out large-denomination notes such as the U.S. $100 bill, the 500-euro note, and the 1,000 Swiss franc note—anything worth $50 or more. (Although I wouldn't suggest following the example of India, which recently phased out 85 percent of its currency supply almost overnight. This move had disastrous effects that could have been avoided if the change had been made more gradually, over a period of years.)

We shouldn't get rid of cash entirely. Even with the rapid evolution of new technologies such as Bitcoin, paper currency provides ordinary citizens with a critical safety valve. The government's objective in regulating new or old transaction technologies should be to discourage wholesale tax evasion and crime while leaving ordinary people a margin of privacy and convenience in their ordinary lives. Putting the economy on a cash diet is a good idea. Literally going cashless is not.

Kenneth Rogoff is a professor of economics at Harvard University and the author of The Curse of Cash.

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Upfront

One Man's Quest to Hack His Own Genes

When Brian Hanley set out to test a gene therapy, he started with himself.

NIV BAVARSKY

Upfront

In a dream Brian Hanley told me about, he's riding a bus when he meets a man in dark leather clothing. Next thing he knows, he is splayed across a tilted metal bed, being electrocuted.

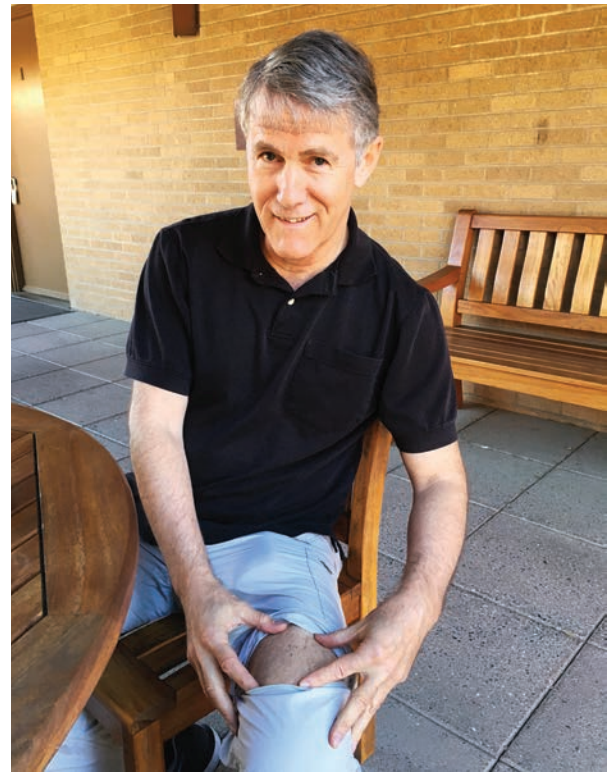
The dream was no doubt connected to events that took place last June at a plastic surgeon's office in Davis, California. At Hanley's request, a doctor had injected into his thighs copies of a gene that Hanley, a PhD microbiologist, had designed and ordered from a research supply company. Then, plunging two pointed electrodes into his leg, the doctor had passed a strong current into his body, causing his muscle cells to open and absorb the new DNA.

The experiment is an example of "do-it-yourself" gene therapy, a risky undertaking that is being embraced by a few daring individuals seeking to develop anti-aging treatments. The gene Hanley added to his muscle cells would make his body produce more of a potent hormone—potentially increasing his strength, stamina, and life span.

Hanley, 60, is the founder of a one-man company called Butterfly Sciences, also in Davis. After encountering little interest from investors for his ideas about using DNA injections to help AIDS patients gain strength, he concluded that he should be the first to try it. "I wanted to prove it, I wanted to do it for myself, and I wanted to make progress," he says.

Most gene therapy involves high-tech, multimillion-dollar experiments carried out by large teams at top medical centers, with an eye to correcting rare illnesses like hemophilia (see "Gene Therapy 2.0," page 48). But Hanley showed that gene therapy can be carried out on the cheap in the same setting as liposuction or a nose job, and might one day be easily accessed by anyone. In an attempt to live longer, some enthusiasts of anti-aging medicines already inject hormones, swallow fullerenes, or gulp megavitamins, sometimes with disregard for mainstream medical thinking. Now unregulated gene therapy could be the next frontier. "I think it's damn crazy," says Bruce Smith, a professor at Auburn University who develops gene therapy for dogs. "But that is human nature, and it's colliding with technology."

To pull off his experiment, Hanley used his scientific knowledge and part of his life savings. He put his insider know-how to work to procure supplies, order blood tests, win the sign-off of an ethics committee, and engage a plastic surgeon who gave him two treatments, a small dose in 2015 and then a larger one last June.



Biologist Brian Hanley shows a tattoo on his thigh marking the location where a "DIY" gene therapy he developed was administered.

COURTESY OF BRIAN HANLEY

Hanley, who drives a battered sedan humming with rave music, fits the profile of an underappreciated genius on a self-improvement quest. He's a prolific online commenter whose arguments touch on everything from radiation to electric cars to street pickup of leaf piles. But his scientific thinking seems sound, and he says the meaning of his dream is straightforward too: he'd become Dr. Frankenstein's monster. "My unconscious is really not that subtle," he says. "I had become something else, not entirely me."

Hanley's undertaking has caught the attention of big-league scientists. His blood is now being studied by researchers at Harvard University at the laboratory of George Church, the renowned genomics expert. Church says he knows of a handful of other cases of DIY gene therapy as well. "And there are probably a lot more," he says, although no one is quite sure, since regulators have not signed off on the experiments. "This is a completely free-form exercise."

Hanley says he did not secure the approval of the U.S. Food and Drug Administration before carrying out his experiment. The agency generally requires companies to seek an authorization called an investigational new drug application before administering any novel drug or gene therapy to people. Hanley argues that his self-experiment didn't pose any risk to the public. That's not to say it wasn't without dangers, such as immune reactions. "I spent years doing very little else other than iterating designs

and thinking of all the ways something could go wrong," he says. The day I met him, Hanley zipped open his cargo pants to show me three black dots tattooed on his left thigh, marking the site of one of the injections. Had the gene therapy gone haywire, he says, his fail-safe option was to have the affected tissue surgically removed.

Most often, gene therapy relies on viruses to shuttle DNA into a person's cells. Hanley opted instead for a simpler method called electroporation. In this procedure, circular rings of DNA, called plasmids, are passed into cells using an electrical current. Once inside, they don't become a permanent part of the person's chromosomes. Instead, they float inside the nucleus. And if a gene is coded into the plasmid, it will start to manufacture proteins. The effect of plasmids is temporary, lasting at most a few months.

Hanley pored over decade-old studies by a company called VGX Animal Health that had tried zapping plasmids into the muscles of cows, dogs with kidney disease, and baby piglets. They'd explored adding extra copies of the gene for growth-hormone-releasing hormone (GHRH)—a molecule that is normally made in the brain. One of its roles is to travel to the pituitary gland, where it acts as a regulator of growth hormone itself, telling the body to make more. It also appears to have an array of other roles, including enhancing the immune system.

Gene therapy can be done on the cheap, in the same setting as a nose job.

"We never did try it in humans, but from everything that I saw in dogs, cats, cattle, pigs, and horses, it seems like a reasonable leap forward," says Douglas Kern, a veterinarian who worked at VGX. "It has very profound positive effects in most species."

Hanley says he designed a plasmid containing the human GHRH gene on his computer and then located a scientific supply company that manufactured the DNA rings for him at a cost of about $10,000. He showed me two vials of the stuff he'd brought along in a thermos, each containing water thickened by half a milligram of DNA.

In planning his study, Hanley skipped some steps that most companies developing a drug would consider essential. In addition to avoiding the FDA, he never tested his plasmid in any animals. He did win clearance for the study from the Institute of Regenerative and Cellular Medicine in Santa Monica, California, a private "institutional review board," or IRB, that furnishes ethics oversight of human experiments.

According to Church's lab, Hanley's levels of GHRH appear elevated, suggesting that the treatment may have had an effect, but it's too early to say definitively. So what happens next? The FDA could get involved, intervening with warning letters or site visits or auditing his ethics board. The plastic surgeon—whose name Hanley asked to keep confidential—could face questions from California's medical board. Or perhaps authorities will simply look the other way because the only person Hanley put at risk was himself.

The kind of attention he is hoping for, he says, is from investors—someone to fund a larger study or perhaps pay for his treatment. Hanley is proud of what he's done. He created a company, secured patents, made new contacts, identified a gene therapy that has plausible benefits for people, and offered himself up as a pioneering volunteer. Doing gene therapy to yourself, he says, "focuses the mind, it really does."

—Antonio Regalado

QUOTED

"Are you happy?"

— What researchers in Europe, using a novel brain-machine interface, asked three completely paralyzed patients. They all said yes.

"This thing that really promoted entrepreneurship and democracy risks becoming the opposite of that."

— Mark Surman, executive director of the Mozilla foundation, on its research that shows the Internet is not open or free enough.

"It will probably disrupt in vitro fertilization as we know it."

— Eli Adashi, a professor of medical science at Brown University and researcher on a new technology that could turn any human cell into a sperm or egg.

BY THE NUMBERS

2,500

Number of homes that Tesla says it could power per day with its new lithium-ion battery storage facility in California.

7.8 million

Metric tons of carbon dioxide that the construction of a wall on the Mexican border will emit, according to the Institute for Sustainable Energy and the Environment at the University of Bath.

10 percent

Drop in average hourly earnings of taxi drivers in cities after Uber arrived, according to a study by the University of Oxford.

$514 million

Amount of money that Snapchat, which plans to go public, lost in 2016.

Upfront

Why Poker Is a Big Deal for Artificial Intelligence

Playing poker involves dealing with imperfect information, which makes the game very complex—like many real-world situations.

As the great Kenny Rogers once said, a good gambler has to know when to hold 'em and know when to fold 'em. It turns out that a computer program can do this better than any human player. At the Rivers Casino in Pittsburgh this winter, a program called Libratus handily outplayed the pros after thousands of games of heads-up, no-limit Texas Hold'em.

It is a huge achievement in artificial intelligence. Poker requires reasoning and intelligence that are difficult for machines to imitate. It is fundamentally different from checkers, chess, or Go, because an opponent's hand remains hidden from view. In such games of "imperfect information," it is enormously complicated to figure out the ideal strategy given every approach your opponent may be taking.

"Poker has been one of the hardest games for AI to crack," says Andrew Ng, chief scientist at Baidu. "There is no single optimal move, but instead an AI player has to randomize its actions so as to make opponents uncertain when it is bluffing."

Libratus was created by Tuomas Sandholm, a professor in the computer science department at Carnegie Mellon University, and his graduate student Noam Brown. Sandholm says it is amazing that humans have been able to outplay computers for so long. The researchers use game theory, or the mathematics of strategic decision making, to find the best strategy given various uncertainties, known as an equilibrium. Because the possibilities are so vast, this usually involves some form of approximation. "Whether a move is good or not depends on things you cannot observe," says Vincent Conitzer, a professor at Duke University who teaches AI and game theory. "This also results in a need to be unpredictable. If you never bluff, you are not a good player. If you always bluff, you are not a good player. Game theory tells you how to randomize your play in a way that is, in a sense, optimal."

Poker involves reasoning and intelligence that have been hard for AI to master.

Last year, Sandholm led the development of a poker-playing program called Claudico, which was soundly beaten in a match against several professional players. He explains that Libratus uses several new advances to achieve such a high level of play. This includes a new equilibrium approximation technique, Sandholm says, as well as several new methods for analyzing possible outcomes as cards are revealed at later stages of a game.

Advances in machine learning and AI have recently given rise to a number of superhuman game-playing programs. Last year, researchers at DeepMind, a subsidiary of Alphabet, developed a program that beat one of the world's best Go players. This achievement was spectacular because Go is extremely complex, and because it is hard to measure progress in the game. The techniques used to build a smarter pokerbot could have many real-world applications. Game theory has already been applied to research on jamming attacks and cybersecurity, automated guidance for taxi services, and robot planning, says Sam Ganzfried, who helped develop Claudico and is now an assistant professor at Florida International University. *—Will Knight*

TO MARKET

Blitab Tablet

Tablet for the Blind

COMPANY:
Blitab

PRICE:
$500

AVAILABILITY:
This summer

COURTESY OF BLITAB

Press a silver button on this device's side, and tiny bumps rise from various holes in a grid that dominates the top half of the gadget. Sixty-five words at a time, the Blitab tablet translates text from the Web and other digital sources into Braille so people who are blind can more easily access anything from mindless jokes to e-books to political news. Other refreshable Braille displays on the market tend to cost thousands of dollars and produce just a few words at a time on one line. The Blitab's Braille display includes 14 rows, each made up of 23 cells with six dots per cell. Underneath the grid are numerous layers of fluids and a special membrane that pushes up the tiny bubbles. *—Rachel Metz*

THE CIO ADVENTURE: NOW, NEXT AND...BEYOND

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This MIT all-star lineup consists of scholars who are affiliated with the MIT Initiative on the Digital Economy (IDE), MIT Sloan Center for Information Systems Research (CISR), and MIT Sloan, as well as the Editor-in-Chief and Publisher of the *MIT Technology Review,* Jason Pontin, and the Editor-in-Chief of the *MIT Sloan Management Review,* Paul Michelman:

- Erik Brynjolfsson
- Kristine Dery
- Nils O. Fonstad
- Stuart Madnick
- Andrew P. McAfee
- Leslie Owens
- Alex Pentland
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Upfront

Very Light Jockeys

At the annual Moreeb Dune Festival in the Liwa desert in the United Arab Emirates, tiny robots fill in for human jockeys in a camel race. The nine-day event celebrating Arabian culture features a mix of 21st-century technologies. Trainers remotely control the robots, which weigh just a few pounds each, as they use a whip to push their camels faster.

Photograph by Karim Sahib

Upfront

One Startup's Vision to Reinvent the Web for Better Privacy

Blockstack's system would let you control your own personal data—for example, by revoking a site's access to it.

Venture capitalist Albert Wenger has done well by investing in Web businesses—he was an early backer of Etsy and Tumblr. But at his urging, Union Square Ventures, where he is a partner, is backing a company founded on the principle that the Web needs a rethink.

"We're living in a time period where the new incumbents like Amazon, Google, and Facebook have firmly established themselves and are near monopolists in their markets," says Wenger. "If we want a long-term, open playing field for innovation, we're going to need new, decentralized infrastructure."

Blockstack recently received $4 million in funding from USV and others to try to establish that more open playing field. The startup is working on open-source software that will create a kind of parallel universe to the Web we know—one where users have more control of their data. Later this year, Blockstack will release software that lets you surf sites and apps created for this new digital domain using your existing Web browser. You will still be able to load sites by clicking links or typing Web addresses, but instead of creating accounts with each site, as people do with Google or Facebook, users of sites built on Blockstack's system will control their own digital identity (or identities). To use a site that needs your information, you will grant access to a profile under your control alone. If you want to stop using a service, you can revoke its access to your profile and data and take it elsewhere. Sites will run all their code on your computer, in the browser.

"We're trying to turn the existing model on its head," says Ryan Shea, CEO and cofounder of Blockstack. "You can try to work with the existing model from within, but sometimes it's easier to step outside of it and build something new from a clean slate." Blockstack's vision is made possible by an identity system built to be independent of any one company, including Blockstack. It uses the digital ledger, or blockchain, underpinning the digital currency Bitcoin to track usernames and associated encryption keys that allow a person to control his or her data and identity. A collective of thousands of computers around the globe maintains the blockchain, and no one entity controls it. Blockstack's system uses the blockchain to record domain names, too, meaning there's no need for an equivalent to ICANN, the body that oversees Web domains today. Software built on top of the name and ID systems gives people control over their data. Microsoft is already collaborating with Blockstack to explore uses for its platform.

Blockstack's tweaks on how the Web functions may seem abstruse. But Shea argues that low-level features of the Web's design, like the lack of a built-in, independent identity system, are at the root of problems such as the dominance of large companies and the latitude they have to make use of user data. He says that companies will still be able to seek profits on the new platform, but power will be tilted more in favor of users.

The dream of a new kind of online sphere faces some significant obstacles, though. Bitcoin's design has proved to lack the capacity needed for a widely used currency—and it's not clear how to build similar, fully decentralized systems that have it, says Emin Gün Sirer, an associate professor at Cornell University. Such systems might also struggle to resolve disputes over things like copyright claims on domain names, he says. *—Tom Simonite*

PATRICK KYLE

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MIT Technology Review

Membership Medicine: The Doctor Will See You Now

Self-Taught Self-Driving Cars Will Soon Hit The Road

Diagnosing Disease with a Face Pic

The Tiny Supercomputer That's All The Rage

10 Breakthrough Technologies of 2016: Where Are They Now?

Upfront

The Robotic Grocery Store of the Future Is Here

Swarm robotics, autonomous delivery vehicles, and machine-learned preferences will help deliver your food faster.

COURTESY OF OCADO

Most people don't buy a jar of relish every week. But when they decide to buy one from Ocado—the world's largest online-only grocery retailer—they don't have to scrabble at the back of the store. Instead, when they select a jar from Ocado's online store, they summon robots and artificial intelligence to have it delivered to their door.

Ocado claims that its 350,000-square-foot warehouse in Dordon, near the U.K.'s second city of Birmingham, is more heavily automated than Amazon's warehouse facilities. The company's task is certainly more challenging in many respects: most of the 48,000 lines of goods that it sells are perishable, and many must be chilled or frozen. Some, such as sushi, must be delivered on the same day they arrive in the warehouse.

That turns storing, picking, and shipping items into a complex, time-constrained optimization problem. But in order for Ocado to grow and turn a profit—which it does, despite a crowded U.K. grocery market—it has to make every step as efficient as possible.

Currently, when a customer orders groceries via Ocado's website, large plastic crates are swiftly filled. The containers are packed by hand, but little legwork is required: 30 kilometers of conveyor belts at the Dordon warehouse carry empty boxes straight to people who work as pickers. They grab items from shelves that are replenished by robots, or from boxes brought out of storage via cranes and conveyors. Ocado's algorithms monitor demand for products and use the information to map out an optimal storage scheme, so that popular items are always within easy reach. Once an order is packed, it's hauled off in a large truck and taken to a distribution center to be loaded into a van. Each van then embarks on a delivery route that can be carefully optimized according to factors such as customer time preferences, traffic, and even weather. But Ocado wants to be faster. "Fractions of a second in our business count," says Paul Clarke, Ocado's chief technology officer. "It's all about how we can shave the next little bit off our process."

So its third warehouse—currently in live trials near Andover, west of London—is being designed from scratch. Its main floor is laid out in a giant grid about the size of a football field, split into washing-machine-size squares. Beneath

each square is a vertical stack of five crates of groceries. On the surface of the grid are up to 1,000 robots, each able to lift crates from below. The robots scuttle around, passing within centimeters of each other, at up to nine miles per hour. Orders relayed via a specially designed 4G network instruct the robots to grab crates and shuttle them to the edge of the grid, where pickers can grab the needed products. The robots work as a swarm: if the required product is four crates down in a stack, for instance, several of them can remove boxes to open the way.

The Andover warehouse, which is likely to enter full service this year, is a trial for an even larger facility in Erith, just outside London, which will begin construction next year. Its storage area will be three times the size. That will make it even more complex to work out where to store goods and retrieve them, using thousands of robots. Clarke says that the computational demands of this optimization problem are bearable, but he adds that the company is investing in GPU-based systems and keeping a watchful eye on quantum computing for the future.

Ocado is working on robotics that could one day pick orders from the crates carried by its swarm of robots, but that's difficult, thanks to the wide variation in the shape of groceries—from, say, a bag of oranges to a bottle of wine. As a result, Clarke says, humans will be involved for the foreseeable future.

He's similarly restrained about automation of the delivery process. While the company is already in discussions with the University of Oxford's self-driving-vehicle spinout Oxbotica—though it won't say about exactly what—Clarke says many customers will continue to prefer a human to deliver their order, even if autonomous vehicles make it possible for robots to take over the job. Still, Ocado's business is by nature one in which robots will ultimately be preferable to humans. When pushed on the impact of automation on employment, Clarke is bullish. He insists that it's a "game that is going to play out regardless," adding that "this is happening on a world stage … if we as a U.K. business don't continue to get better using automation, somebody else will, and we're determined not to let that happen." The customer experience, meanwhile, will benefit from AI systems being built by Ocado's developers. "With more data comes greater intelligence—because that's the food of machine learning," says Clarke. The company uses machine learning to spot missing items in a shop, populate a basket of groceries on the basis of learned preferences, and even suggest versions of products that are lower in salt or sugar.

In the grocery delivery business, fractions of a second count.

Over time, Ocado plans to streamline the ordering process as far as it possibly can. Clarke suggests that the company could acquire consumption data from your smart fridge, listen to what recipes you're talking about via a smart assistant like Amazon's Alexa, and even mine your calendar for data so it knows you'll be cooking for friends next weekend. Ultimately, he says, it would like for "the right groceries to turn up, at the right time, as if by magic, without you even having to ask for them."

It's not the only company asking food shoppers to sacrifice anonymity for convenience. Amazon's new Go convenience store, for instance, allows shoppers to scan their phone, pick up food from the shelf, and walk straight out, paying later because the company knows just what they took.

Still, if customers can stomach the loss of privacy, Ocado offers something valuable in return. "We can free people up," says Clarke, "so that they have more time to experiment and experience the delight of food." *—Jamie Condliffe*

TO MARKET

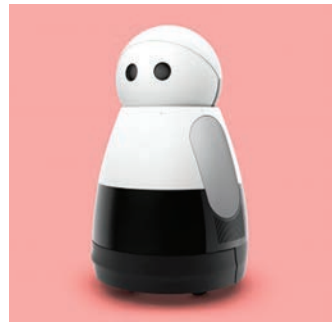
Kuri

Home robot

COMPANY:
Mayfield Robotics

PRICE:
$699

AVAILABILITY:
Late 2017



COURTESY OF KURI

Kuri looks up at me and squints as if in a smile. Then the robot rolls across the floor, emitting a few R2-D2-like beeps. Mayfield Robotics built Kuri as the next step in home robotics, ready to offer companionship and entertainment with personality. The 20-inch-tall robot is essentially an Amazon Alexa on wheels, letting users play music or control their smart devices from anywhere in the home. It can also live-stream video of your home for surveillance purposes. Behind one of Kuri's eyes is a 1080p camera, and users can access a live stream from an app. Kuri comes across as lovable but simple, so there's no reason to expect it to do more than simple jobs. *—Signe Brewster*

Upfront

SAM D'ORAZIO

Eyeing a Dropbox IPO

Can the tech unicorn cash in on corporate users?

Of the big IPOs expected to occur this year, Dropbox's could be one of the most intriguing. When Dropbox last raised money, in 2014, it was valued at a hefty $10 billion. But large investors such as Fidelity and T. Rowe Price slashed the value of the Dropbox shares on their books by as much as 50 percent in 2015. The key concern: could a company whose free file storage service is used by hundreds of millions of people find enough paying customers to make a great business?

Investors may be in for a pleasant surprise. According to the company, sales are now running at more than $1 billion a year, up from around $400 million in 2014. That's thanks in part to growing sales of Dropbox Business, a souped-up version of the free app that costs $150 per employee per year. The company has been cash-flow positive since early 2016, even as it has made heavy investments in engineering, sales, and IT infrastructure.

Now CEO and cofounder Drew Houston is leading a new strategic charge. In addition to selling utilities to keep digital files safe and accessible, Dropbox intends to offer software that businesspeople use for hours each day to create content and get work done. "This is a mature, very, very powerful software company," says Bryan Schreier, a partner with venture capital firm Sequoia Capital, which was an early investor in the company.

That doesn't mean Dropbox will live up to that heady $10 billion valuation, which even at the time was widely seen as a sign of a bubble about to burst. Even at an annualized revenue of $1 billion, investors would need to think the company is worth 10 times its current sales on the day it goes public. These days, the average cloud software company trades at just 4.7 times revenue, according to Bessemer Venture Partners.

Still, Schreier and other investors insist they are no longer worried about

Dropbox's fundamental business model. About 10 million new people start using the free consumer product every month. An increasing percentage of those users sign up for the $100-a-year Pro version, which offers more storage and sharing features. Many of those Pro customers use Dropbox at work, and once their employers realize how popular it is, they are more likely to step up to Dropbox Business, which is designed for use by teams rather than individuals. So far more than 200,000 companies have signed up for Dropbox Business, up from 50,000 in 2014. While most are small and medium-sized companies, a few big companies such as Expedia and News Corp. have more than 10,000 seats.

A successful push into productivity and collaboration software could give corporate customers much more to buy from Dropbox. The first example is Paper, which provides a kind of virtual white space where employees and contractors can share Excel spreadsheets, Google Docs, and other digital assets regardless of what device they are using. The idea is to tie together scores of different productivity tools and fold in management tools to help teams keep projects on track. Paper has been in beta since late 2015 and officially launched in January. "In five years, you could start a business on Dropbox: that is something we aspire to," says chief operating officer Dennis Woodside, who declined to comment on IPO plans.

Dropbox is far from the only company looking to change the way work is done. Google offers G Suite, which contains business versions of apps such as Google Docs and Gmail. Facebook has a collaboration service called Workplace. Microsoft is improving its cloud offerings as it seeks to defend the massive market share earned with its Windows and Office monopolies. Box has strong traction with companies in highly regulated industries like health care and financial services, while younger providers such as Asana, Atlassian, and Slack already handle elements of what Dropbox aims to do. According to Gartner analyst Karen Hobert, there are 130 companies just in the electronic file storage and sync market.

Yet even rivals see Dropbox as a likely survivor of the inevitable consolidation. The overall market opportunity for productivity and collaboration tools is $30 billion, if you replace all those PC disk drives and traditional Windows or Mac programs with cloud-based alternatives. "That's an order of magnitude more than the combined revenue of all the players today," says Box chief executive officer Aaron Levie. "As everything moves to the cloud, there's going to be plenty of opportunity."

The tools workers will use in five years will be very different from today's.

Dropbox has been bulking up for this opportunity since 2014, when Houston hired Woodside. A former McKinsey consultant, Woodside joined Google in 2003 as an operations expert before running U.S. sales and then the Motorola Mobility cell-phone division. At Dropbox, he's hired more than 200 salespeople, up from zero when the company relied solely on Internet clicks. The engineering team has more than doubled to more than 1,000 members, large by any measure. And he has overseen a massive, risky IT overhaul. While most companies are moving more of their business onto public cloud platforms like the one run by Amazon Web Services, Dropbox has shifted billions of its U.S. customers' files away from Amazon's platform to three of its own data centers. That way, Dropbox can tweak its network to cut the time it takes to store and sync traffic.

The result is more of a traditional enterprise software company than the hyper-efficient app maker Houston founded in 2007. The idea for the company came when Houston realized during a long bus ride that he'd forgotten the USB drive with his work files at home. The resulting cloud-storage app was a sensation with people who felt his pain. By 2012, Dropbox had 100 million registered users.

Then things got difficult. Giants such as Amazon, Apple, Microsoft, and Google began giving away cloud storage capacity as a way to sweeten other offerings. As prices collapsed, cloud storage specialists faced an existential threat.

A successful move by Dropbox into the huge market for productivity and collaboration software could brighten the outlook, but it will require the company to pull off two tough transformations at once. Dropbox is still evolving from a maker of a free consumer app to a corporate IT infrastructure company. Now it must also move from selling technology that's designed to be as invisible as possible to making products people use throughout much of their day. Its competitor Box provides a cautionary tale. It introduced a Paper-like product three years ago called Box Notes. But Levie admits that its reception has been less than overwhelming. Box relaunched Notes with new features earlier this year.

Woodside responds that few companies have the scale, the technical expertise, and the brand to pull off its ambitious plans. "There's close to two billion knowledge workers in the world, and I know this much: the tools they'll be using in five years are not the ones they're using today," he says. "Is the number 500 million? A billion? I don't know. But we have a shot." *—Peter Burrows*

Upfront

Hand Over the Data

Governments are getting more user data from Internet companies every year, as people leave more traces of their lives online and law enforcement officials become increasingly reliant on that information. These figures, from Google's "transparency report," show how many times authorities in the U.S. and other countries have requested evidence about people who use the company's services.

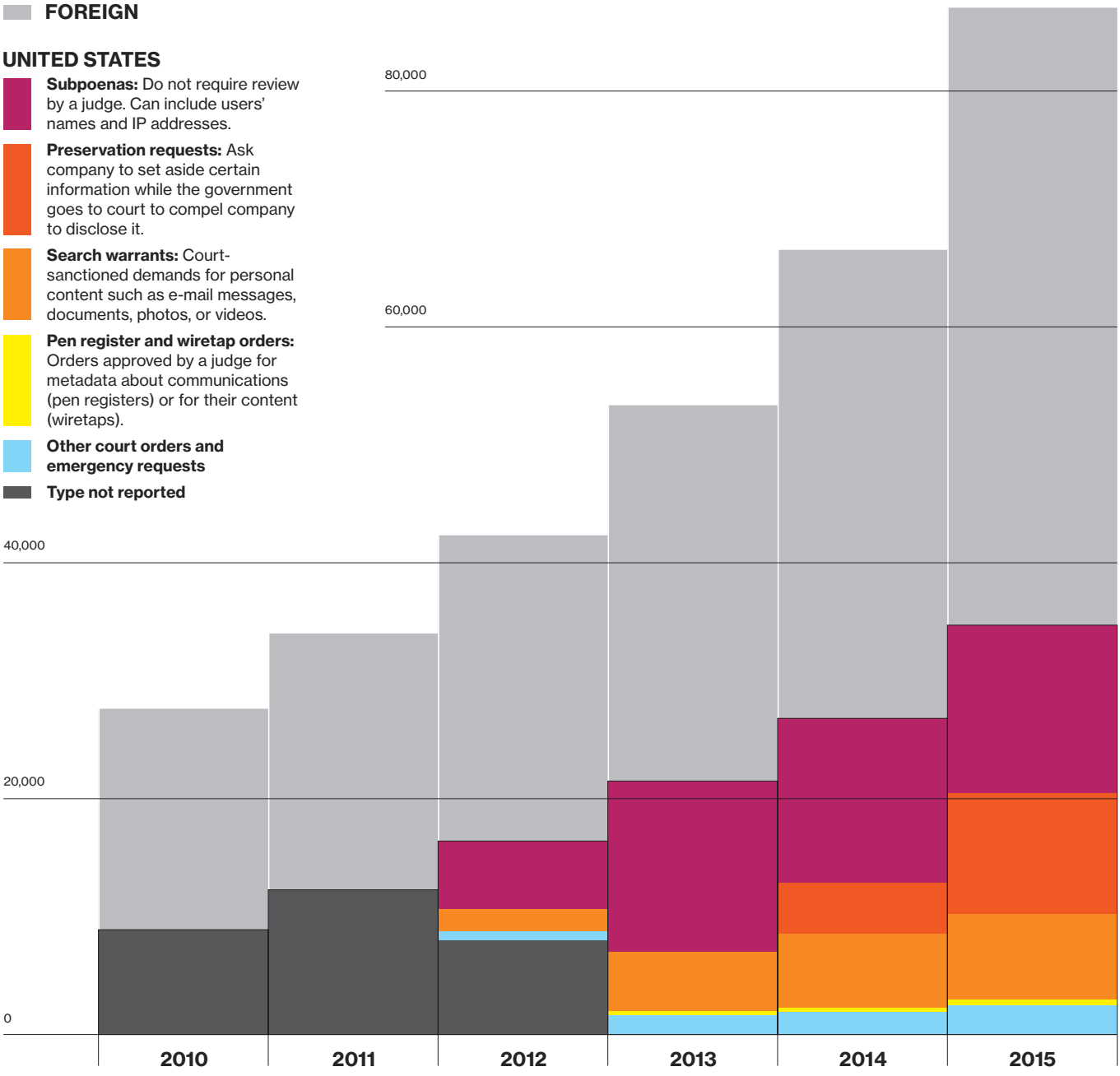


ILLUSTRATION BY LUKE SHUMAN; DATA FROM GOOGLE

Focus on the Technologies That Matter Most

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Q+A

Jessica Brillhart

Jessica Brillhart is the principal filmmaker for virtual reality at Google, where she enjoys one of the most creative jobs in Silicon Valley. She makes VR experiences (including *World Tour*, the first film made with Google's Jump system, a circular 16-camera rig designed to capture VR films) and conventional movies (or "flatties," as she calls them), and she evaluates new VR technologies, such as Google's own Cardboard, a cheap headset that works with smartphones. (For more on the challenge of telling stories in VR, see "Virtually There," page 96.) She spoke to *MIT Technology Review*'s editor in chief, Jason Pontin.

What does the principal filmmaker for VR at Google do?
I see the technologies we're building at Google, specifically in VR. And I ask what I can do with them creatively. I mediate between the engineers and creative people, and I make stuff in the process.

When did you first encounter virtual reality?
One day, I visited an engineering team that was building a 360° camera, and I saw their demos, and it was the stuff we're used to now—musicians in 360 degrees—and I thought, "That's kind of interesting." But there was one demo that they were hesitant to show me because it was the first they ever filmed. It was of all the engineers in the office turning on the rig for the first time. And they were so happy! I just loved the goofy looks on their faces. At first they were just looking around. Like, "Is it working? We don't know." And then suddenly they were throwing their arms in the air. And you felt delighted because they were just so pleased that it worked. And I knew I had seen something that filmmaking had a really hard time doing. Probably could never do.

Can VR support a story with a through line?
I'm pretty harsh about this question, because I think emphasizing storytelling isn't right. Storytelling is the product of film as a medium. In *Man with a Movie Camera* [1929], Dziga Vertov went out with a camera and filmed everyday stuff, and then he and his wife found a way to edit it together. And he wanted to dismiss all the film that came before him, because he thought it was just theater. Vertov's idea was that the camera was a disembodied eye: a detached thing that could follow a horse, or be under a train, or throw you over a building. It can show a world previously unknown to you. But it's *Vertov's* perspective on the world.

With VR it's about *you* being convinced that you're physically in another space. VR is an embodied medium: creators are taking that detached eye and reattaching it to someone's face. VR reminds us of the nuances of experiences, what connects people with each other, with places, with things in the real world. And that to me is the key to really understanding

TIM BARBER

what kind of storytelling could even exist in a VR space.

Who is doing for VR what Gregg Toland, who invented the deep focus used in *Citizen Kane*, did for film?

From a cinematics standpoint, Felix & Paul are technically excellent. But if anyone is going to be remembered, it's a kid from the Czech Republic named Tomáš Mariančík who created an experience called *Sightline: The Chair*. The idea is: the world evolves as you spin. So I'm looking at a candle. If I look away and then look back, the candle will be a cube. And I'll look back at the cube and it will be a building, and then a tree. Everything changes, everything evolves. The only way you can stop it is by not moving. But you can only do that for so long before you move a little bit, and on it goes. It's kind of drug-like, where suddenly you get beyond your anxieties and you feel euphoric.

VR users often are curious about what they want to see—and resist what the creator intends them to see.

I love defiance. If I'm in a space and there's a large red arrow pointing to a door, it's awful. I don't want to go there. I've gotten to know Rand and Robyn Miller, the co-creators of Myst. Robyn said he would go into every experience and see where the creator wanted him to look. But Robyn would inspect whatever he was meant to see and then turn in the opposite direction. He said you'd be shocked by how little there is there. And so I started doing that, too. I feel, "Don't put me in a space and say I have to look where you want. That's not how this new thing works."

Is there a better way?

There's a scene in an experience called Residence where a young girl is playing violin, kind of poorly. That's the whole scene, but if you turn around you can see her parents looking in at the doorway and you can hear her behind you playing badly, and you're watching their reaction.

Do you try to be careful about what you make your visitors experience?

I look to gaming for a lot of clues. Most games won't immediately throw you into the worst possible fit. No, they'll say, "Here are some mushrooms and if you step on them they'll die, and if you eat them you'll grow." And you progressively gain strength and get to the boss levels. I believe you have to create similar cadences in VR.

Will people use VR to record home videos?

Yes, but I'm still figuring out whether or not that's a good thing. It might be overwhelming. Think of everything you forget about a birthday party when you're a kid. But now the rig would capture everything. You could watch someone you loved respond the way she used to, or eat cake a certain way. It is going to be interesting to see what happens when we aren't able to forget anything anymore.

Will VR supplant film?

My mom saw a piece I did for the first time. She came out of the experience and she said, "Oh my gosh. This transports your *brain*." Skeptical people come into my studio and they say, "What you got?" They go into the experience and their jaw just drops. VR is its own medium. It's not going to hurt any other medium. You're going to see a lot of traditional-media folks trying to get it to work in their domain, and they may succeed. I don't know. But something really special is happening.

10

These technologies all have staying power. They will affect the economy and our politics, improve medicine, or influence our culture.

Breakthrough TECHNOLOGIES

Some are unfolding now; others will take a decade or more to develop. But you should know about all of them right now.

THE DISPLAY TEXT IN THIS SECTION IS SET LYDIA (COLOPHON FOUNDRY, 2010), A BOLD, CONDENSED ITERATION OF WARREN CHAPPELL'S LYDIAN FROM 1938. AND FERRY (LETTERS FROM SWEDEN, 2014), BASED ON EARLY 20TH CENTURY SWEDISH HARBOR LETTERING

Reinforcement LEARNING

BREAKTHROUGH
An approach to artificial intelligence that gets computers to learn like people, without explicit instruction.

WHY IT MATTERS
Progress in self-driving cars and other forms of automation will slow dramatically unless machines can hone skills through experience.

KEY PLAYERS
- DeepMind
- Mobileye
- OpenAI
- Google
- Uber

AVAILABILITY
1 to 2 years

By WILL KNIGHT

By experimenting, computers are figuring out how to do things that no programmer could teach them.

Inside a simple computer simulation, a group of self-driving cars are performing a crazy-looking maneuver on a four-lane virtual highway. Half are trying to move from the right-hand lanes just as the other half try to merge from the left. It seems like just the sort of tricky thing that might flummox a robot vehicle, but they manage it with precision.

I'm watching the driving simulation at the biggest artificial-intelligence conference of the year, held in Barcelona this past December. What's most amazing is that the software governing the cars' behavior wasn't programmed in the conventional sense at all. It learned how to merge, slickly and safely, simply by practic-

SEYMOUR CHWAST


CHWAST

ing. During training, the control software performed the maneuver over and over, altering its instructions a little with each attempt. Most of the time the merging happened way too slowly and cars interfered with each other. But whenever the merge went smoothly, the system would learn to favor the behavior that led up to it.

This approach, known as reinforcement learning, is largely how AlphaGo, a computer developed by a subsidiary of Alphabet called DeepMind, mastered the impossibly complex board game Go and beat one of the best human players in the world in a high-profile match last year. Now reinforcement learning may soon inject greater intelligence into much more than games. In addition to improving self-driving cars, the technology can get a robot to grasp objects it has never seen before, and it can figure out the optimal configuration for the equipment in a data center.

These images are from the Mobileye vision system for cars, which will benefit from reinforcement learning.

COURTESY OF MOBILEYE

Reinforcement learning copies a very simple principle from nature. The psychologist Edward Thorndike documented it more than 100 years ago. Thorndike placed cats inside boxes from which they could escape only by pressing a lever. After a considerable amount of pacing around and meowing, the animals would eventually step on the lever by chance. After they learned to associate this behavior with the desired outcome, they eventually escaped with increasing speed.

Some of the very earliest artificial-intelligence researchers believed that this process might be usefully reproduced in machines. In 1951, Marvin Minsky, a student at Harvard who would become one of the founding fathers of AI as a professor at MIT, built a machine that used a simple form of reinforcement learning to mimic a rat learning to navigate a maze. Minsky's Stochastic Neural Analogy Reinforcement Computer, or SNARC, consisted of dozens of tubes, motors, and clutches that simulated the behavior of 40 neurons and synapses. As a simulated rat made its way out of a virtual maze, the strength of some synaptic connections would increase, thereby reinforcing the underlying behavior.

There were few successes over the next few decades. In 1992, Gerald Tesauro, a researcher at IBM, demonstrated a program that used the technique to play backgammon. It became skilled enough to rival the best human players, a landmark achievement in AI. But reinforcement learning proved difficult to scale to more complex problems. "People thought it was a cool idea that didn't really work," says David Silver, a researcher at DeepMind in the U.K. and a leading proponent of reinforcement learning today.

That view changed dramatically in March 2016, however. That's when AlphaGo, a program trained using reinforcement learning, destroyed one of the best Go players of all time, South Korea's Lee Sedol. The feat was astonishing, because it is virtually impossible to build a good Go-playing program with conventional programming. Not only is the game extremely complex, but even accomplished Go players may struggle to say why certain moves are good or bad, so the principles of the game are difficult to write into code. Most AI researchers had expected that it would take a decade for a computer to play the game as well as an expert human.

THE TECHNOLOGY
can get a robot to grasp objects it has never seen before.

JOSTLING FOR POSITION

Silver, a mild-mannered Brit who became fascinated with artificial intelligence as an undergraduate at the University of Cambridge, explains why reinforcement learn-

Reinforcement learning led to AlphaGo's stunning victory over a human Go champion last year.

COURTESY OF DEEPMIND

ing has recently become so formidable. He says that the key is combining it with deep learning, a technique that involves using a very large simulated neural network to recognize patterns in data (see "10 Breakthrough Technologies 2013: Deep Learning").

Reinforcement learning works because researchers figured out how to get a computer to calculate the value that should be assigned to, say, each right or wrong turn that a rat might make on its way out of its maze. Each value is stored in a large table, and the computer updates all these values as it learns. For large and complicated tasks, this becomes computationally impractical. In recent years, however, deep learning has proved an extremely efficient way to recognize patterns in data, whether the data refers to the turns in a maze, the positions on a Go board, or the pixels shown on screen during a computer game.

In fact, it was in games that DeepMind made its name. In 2013 it published details of a program capable of learning to play various Atari video games at a superhuman level, leading Google to acquire the company for more than $500 million in 2014. These and other feats have in turn inspired other researchers and companies to turn to reinforcement learning. A number of industrial-robot makers are testing the approach as a way to train their machines to perform new tasks without manual programming. And researchers at Google, also an Alphabet subsidiary, worked with DeepMind to use deep reinforcement learning to make its data centers more energy efficient. It is difficult to figure out how all the elements in a data center will affect energy usage, but a reinforcement-learning algorithm can learn from collated data and experiment in simulation to suggest, say, how and when to operate the cooling systems.

But the setting where you will probably most notice this software's remarkably humanlike behavior is in self-driving cars. Today's driverless vehicles often falter in complex situations that involve interacting with human drivers, such as traffic circles or four-way stops. If we don't want them to take unnecessary risks, or to clog the roads by being overly hesitant, they will need to acquire more nuanced driving skills, like jostling for position in a crowd of other cars.

The highway merging software was demoed in Barcelona by Mobileye, an Israeli automotive company that makes vehicle safety systems used by dozens of carmakers, including Tesla Motors (see "50 Smartest Companies 2016"). After screening the merging clip, Shai Shalev-Shwartz, Mobileye's vice president for technology, shows some of the challenges self-driving cars will face: a bustling roundabout in Jerusalem; a frenetic intersection in Paris; and a hellishly chaotic scene from a road in India. "If a self-driving car follows the law precisely, then during rush hour I might wait in a merge situation for an hour," Shalev-Shwartz says.

Mobileye plans to test the software on a fleet of vehicles in collaboration with BMW and Intel later this year. Both Google and Uber say they are also testing reinforcement learning for their self-driving vehicles.

Reinforcement learning is being applied in a growing number of areas, says Emma Brunskill, an assistant professor at Stanford University who specializes in the approach. But she says it is well suited to automated driving because it enables "good sequences of decisions." Progress would proceed much more slowly if programmers had to encode all such decisions into cars in advance.

But there are challenges to overcome, too. Andrew Ng, chief scientist at the Chinese company Baidu, warns that the approach requires a huge amount of data, and that many of its successes have come when a computer could practice relentlessly in simulations. Indeed, researchers are still figuring out just how to make reinforcement learning work in complex situations in which there is more than one objective. Mobileye has had to tweak its protocols so a self-driving car that is adept at avoiding accidents won't be more likely to cause one for someone else.

When you watch the outlandish merging demo, it looks as though the company has succeeded, at least so far. But later this year, perhaps on a highway near you, reinforcement learning will get its most dramatic and important tests to date.

PRODUCT PHOTOS BY LEONARD GRECO

BREAKTHROUGH
Consumer cameras that produce 360° images, providing a realistic sense of events or places.

WHY IT MATTERS
Photos and videos with this perspective could become the new standard for everything from news coverage to vacation shots.

KEY PLAYERS
- Ricoh
- Samsung
- 360fly
- JK Imaging (maker of Kodak Pixpro digital cameras)
- IC Real Tech (maker of the ALLie camera)
- Humaneyes Technologies

AVAILABILITY
Now

THE 360-Degree Selfie

Inexpensive cameras that make spherical images are opening a new era in photography and changing the way people share stories.

By **ELIZABETH WOYKE**

Seasonal changes to vegetation fascinate Koen Hufkens. So last fall Hufkens, an ecological researcher at Harvard, devised a system to continuously broadcast images from a Massachusetts forest to a website called VirtualForest.io. And because he used a camera that creates 360° pictures, visitors can do more than just watch the feed; they can use their mouse cursor (on a computer) or finger (on a smartphone or tablet) to pan around the image in a circle or scroll up to view the forest canopy and down to see the ground. If they look at the image through a virtual-reality headset they can rotate the photo by moving their head, intensifying the illusion that they are in the woods.

Hufkens says the project will allow him to document how climate change is affecting leaf development in New England. The total cost? About $550, including $350 for the Ricoh Theta S camera that takes the photos.

We experience the world in 360 degrees, surrounded by sights and sounds. Until recently, there were two main options for shooting photos and video that captured that context: use a rig to position multiple cameras at different angles with overlapping fields of view or pay at least $10,000 for a special camera. The production process was just as cumbersome and generally took multiple days to complete. Once you shot your footage, you had to transfer the images to a computer; wrestle with complex, pricey software to fuse them into a seamless picture; and then convert the file into a format that other people could view easily.

Today, anyone can buy a decent 360° camera for less than $500, record a video

COURTESY OF ALLIE CAMERA

Chicago's Millennium Park captured by the ALLie camera.

ALLIE CAMERA
It uses technology originally developed for the surveillance industry and can capture images in low light.

Ballet dancers captured by the Samsung Gear 360.

The 360° format is so compelling that it could become a new standard FOR RAW FOOTAGE OF NEWS EVENTS.

within minutes, and upload it to Facebook or YouTube. Much of this amateur 360° content is blurry; some of it captures 360 degrees horizontally but not vertically; and most of it is mundane. (Watching footage of a stranger's vacation is almost as boring in spherical view as it is in regular mode.) But the best user-generated 360° photos and videos—such as the Virtual Forest—deepen the viewer's appreciation of a place or an event.

Journalists from the *New York Times* and Reuters are using $350 Samsung Gear 360 cameras to produce spherical photos and videos that document anything from hurricane damage in Haiti to a refugee camp in Gaza. One *New York Times* video that depicts people in Niger fleeing the militant group Boko Haram puts you in the center of a crowd receiving food from aid groups. You start by watching a man heaving sacks off a pickup truck and hearing them thud onto the ground. When you turn your head, you see the throngs that have gathered to claim the food and the makeshift carts they will use to transport it. The 360° format is so compelling that it could become a new standard for raw footage of news events—something that Twitter is trying to encourage by enabling live spherical videos in its Periscope app.

Or consider the spherical videos of medical procedures that the Los Angeles startup Giblib makes to teach students about surgery. The company films the

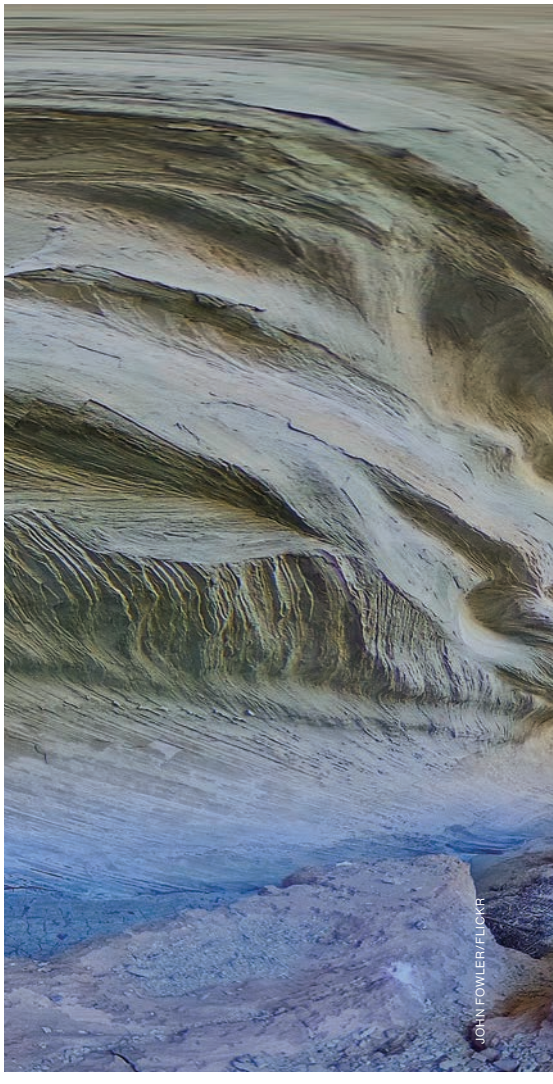
COURTESY OF SAMSUNG

SAMSUNG GEAR 360
Samsung has given these cameras to *New York Times* and Reuters journalists who are producing 360° news coverage.

RICOH THETA S

Ricoh put the image sensors on the camera's sides instead of behind its lenses, making its thin shape possible.

Utah's Sidestep Canyon captured by the Ricoh Theta S.



JOHN FOWLER/FLICKR

operations by attaching a $500 360fly 4K camera, which is the size of a baseball, to surgical lights above the patient. The 360° view enables students to see not just the surgeon and surgical site, but also the way the operating room is organized and how the operating room staff interacts.

Meanwhile, inexpensive 360° cameras such as Kodak's $450 Pixpro SP360 4K are popping up on basketball backboards, football fields, and hockey nets during practice for professional and collegiate teams. Coaches say the resulting videos help players visualize the action and prepare for games in ways that conventional sideline and end-zone videos can't.

COMPONENT INNOVATIONS

These applications are feasible because of the smartphone boom and innovations in several technologies that combine images from multiple lenses and sensors. For instance, 360° cameras require more horsepower than regular cameras and generate more heat, but that is handled by the energy-efficient chips that power smartphones. Both the 360fly and the $499 ALLie camera use Qualcomm Snapdragon processors similar to those that run Samsung's high-end handsets.

Camera companies also benefited in recent years from smartphone vendors' continuous quest to integrate higher-quality imaging into their gadgets. The competition forced component makers like Sony to shrink image sensors and ensure that they offered both high resolution and good performance in low light. As the huge smartphone market helped bring down component prices, 360°-camera makers found it possible to price their devices accessibly, often at less than

360FLY 4K
Dustproof and water-resistant, it's often used to record extreme sports.

Bicyclists in Taiwan captured by the 360fly 4K.

KIN MUN LEE/FLICKR

TECHNOLOGIES.

These applications are possible because of the smartphone boom and innovations in computer vision

$500. "There are sensors that now cost $1 instead of $1,000 because they're used in smartphones, which have incredible economies of scale," says Jeffrey Martin, the CEO of a 360°-camera startup called Sphericam. Advances in optics played a part as well. Unlike traditional cameras, which have fairly narrow fields of view, 360° cameras sport exaggerated fish-eye lenses that require special optics to align and focus images across multiple points.

Most 360° cameras lack displays and viewfinders. To compensate, camera makers developed apps that you can download to your phone to compose shots and review the resulting images. The cameras connect to the apps wirelessly, and many of them allow you to upload photos and video directly from your phone to Facebook and YouTube. In turn, those sites have made it possible over the past year for people not just to post recorded 360° content but to live-stream 360° videos as well.

Because creating 360° content requires stitching together multiple images, doing it on the fly for live streaming represents an impressive technical achievement. Computer-vision algorithms have simplified the process so that it can be done on the camera itself, which in turn allows people to live-stream video

with minimal delays. (It helps that most consumer-grade cameras have only two lenses and thus one stitch line. Professional versions can have six to 24 lenses.) The ALLie camera supports fast stitching and live-streaming, as do Ricoh's upcoming Ricoh R development kit camera and Kodak's Orbit360 4K, which will be available later this year for $500.

Spherical cameras represented 1 percent of worldwide consumer camera shipments in 2016 and are set to reach 4 percent in 2017, according to the research firm Futuresource Consulting. The popularity of these devices will benefit the virtual-reality industry as well as camera makers. You don't need special VR gear to view spherical videos, but YouTube says many people look at them on smartphones slipped into VR headsets, such as Google's Cardboard and Daydream devices. And more people experimenting with 360° cameras means more content for other people to watch in VR.

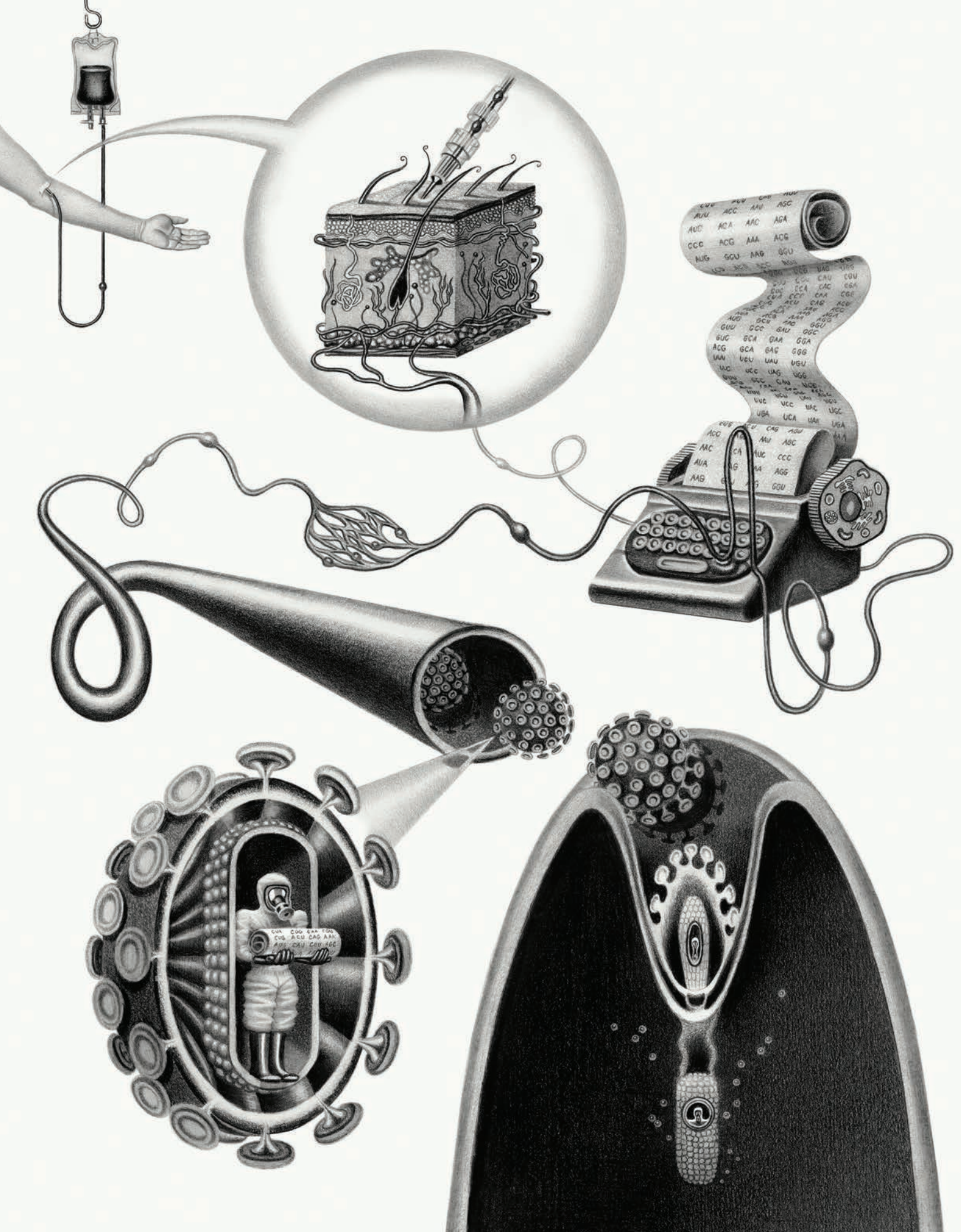
In fact, John Carmack, the chief technology officer of Facebook's Oculus VR subsidiary, has predicted that people will spend less than 50 percent of their VR time playing games. Instead, they may don VR headsets to do things like virtually attend a wedding.

Once people discover spherical videos, research suggests, they shift their viewing behavior quickly. The company Humaneyes, which is developing an $800 camera that can produce 3-D spherical images, says people need to watch only about 10 hours of 360° content before they instinctively start trying to interact with all videos. When you see 360° imagery that truly transports you somewhere else, you want it more and more.

TOM POOLE/FLICKR

An urban scene captured by the Kodak Pixpro SP360 4K.

KODAK PIXPRO SP360 4K
It can be mounted on a drone to produce aerial 360° videos.



BREAKTHROUGH
First gene therapies on track for approval in the U.S. More are on the way.

WHY IT MATTERS
Thousands of diseases stem from an error in a single gene. New treatments could cure them.

KEY PLAYERS
- Spark Therapeutics
- BioMarin
- BlueBird Bio
- GenSight Biologics
- UniQure

AVAILABILITY
Now

Gene Therapy 2.0

Scientists have solved fundamental problems that were holding back cures for rare hereditary disorders. Next we'll see if the same approach can take on cancer, heart disease, and other common illnesses.

By **EMILY MULLIN**

ARMANDO VEVE

When Kala Looks gave birth to fraternal twin boys in January 2015, she and her husband, Philip, had no idea that one of them was harboring a deadly mutation in his genes.

At three months old, their son Levi was diagnosed with severe combined immune deficiency, or SCID, which renders the body defenseless against infections. Levi's blood had only a few immune cells essential to fighting disease. Soon he would lose them and have no immune system at all.

Kala and Philip frantically began sanitizing their home to keep Levi alive. They got rid of the family cat, sprayed every surface with Lysol, and boiled the twins' toys in hot water. Philip would strap on a surgical mask when he came home from work.

At first, Kala and Philip thought their only option was to get Levi a bone marrow transplant, but they couldn't find a match for him. Then they learned about an experimental gene therapy at Boston Children's Hospital. It was attempting to treat children like Levi by replacing the gene responsible for destroying his immune system.

"I thought, this isn't real," Kala says. "There's no way this could work."

Nonetheless, the Lookses flew from their home in Michigan to Boston in May 2015. Days later, Levi got an infusion of the therapy into his veins. He has been a normal boy ever since—and he has even grown larger than his twin brother. Babies born with SCID typically didn't survive past two years old. Now, a one-time treatment offers a cure for patients like Levi Looks.

Researchers have been chasing the dream of gene therapy for decades. The idea is elegant: use an engineered virus to deliver healthy copies of a gene into patients with defective versions. But until recently it had produced more disappointments than successes. The entire field was slowed in 1999 when an 18-year-old patient with a liver disease, Jesse Gelsinger, died in a gene-therapy experiment.

But now, crucial puzzles have been solved and gene therapies are on the verge of curing devastating genetic disorders. Two gene therapies for inherited diseases—Strimvelis for a form of SCID and Glybera for a disorder that makes fat build up in the bloodstream—have won regulatory approval in Europe. In the United States, Spark Therapeutics could be the first to market; it has a treatment

GENE-THERAPY TIME LINE

1960S
The idea of gene therapy arises when scientists discover enzymes that can be used to cut DNA sequences and stitch them together in test tubes.

1970S
Scientists experiment with using viruses to introduce new genes into animals.

1990
A four-year-old girl (pictured at lower right in 1992) is treated for SCID, a genetic disease that would have left her defenseless against infections. But other children with the disease will later develop leukemia from a different gene therapy.

1999
Jesse Gelsinger, 18, becomes the first patient to die in a clinical trial for gene therapy.

CHRIS WARE /GETTY; FOX PHOTOS /GETTY; COURTESY OF THE IMMUNE DEFICIENCY FOUNDATION; COURTESY OF THE GELSINGER FAMILY

for a progressive form of blindness. Other gene therapies in development point to a cure for hemophilia and relief from an incapacitating skin disorder called epidermolysis bullosa.

Fixing rare diseases, impressive in its own right, could be just the start. Researchers are studying gene therapy in clinical trials for about 40 to 50 different diseases, says Maria-Grazia Roncarolo, a pediatrician and scientist at Stanford University who led early gene-therapy experiments in Italy that laid the foundation for Strimvelis. That's up from just a few conditions 10 years ago. And in addition to treating disorders caused by malfunctions in single genes, researchers are looking to engineer these therapies for more common diseases, like Alzheimer's, diabetes, heart failure, and cancer. Harvard geneticist George Church has said that someday, everyone may be able to take gene therapy to combat the effects of aging.

Early gene therapies failed in part because of the delivery mechanism. In 1990, a four-year-old girl with a form of SCID was treated by scientists at the National Institutes of Health, who extracted white blood cells from her, inserted normal copies of her faulty gene into them, then injected her with the corrected cells. But patients later treated for a different type of SCID went on to develop leukemia. The new genetic material and the virus used to carry it into cells were delivered to the wrong part of the genome, which switched on cancer-causing genes in some patients. In Gelsinger's case, the virus used to transport functioning genes into his cells made his immune system go into overdrive, leading to multiple organ failure and brain death.

Gene-therapy researchers have surmounted many of those early problems by using viruses that are more efficient at transporting new genetic material into cells.

But several challenges remain. While gene therapies have been developed for several relatively rare diseases, creating such treatments for more common diseases that have complex genetic causes will be far more difficult. In diseases like SCID and hemophilia, scientists know the precise genetic mutation that is to blame. But diseases like Alzheimer's, diabetes, and heart failure involve multiple genes—and the same ones aren't all involved in all people with those conditions.

Nonetheless, for Kala and Philip Looks, the success of gene therapy is already real. A treatment they had never heard of rid their child of a horrific disease.

2007-2008
Patients with an inherited retinal disease called Leber's congenital amaurosis appear to have improved vision after treatment with a gene therapy. However, years later, researchers will report in the *New England Journal of Medicine* that some patients' eyesight has begun to wane.

2012
The European Medicines Agency approves the first gene therapy for an inherited disease. Called Glybera, the drug treats lipoprotein lipase deficiency, which causes fat to build up in the blood.

MAY 2016
European regulators approve Strimvelis, the second gene therapy for an inherited disease, to treat a type of SCID.

2017 OR 2018
A gene therapy for an inherited disease could be approved in the U.S. for the first time.

MIKAEL HÄGGSTRÖM; COURTESY OF UNIQURE; MYSTÈRE MARTIN / WIKIMEDIA; ERIC PIERMONT/ GETTY

Hot SOLAR Cells

BREAKTHROUGH
A solar power device that could theoretically double the efficiency of conventional solar cells.

WHY IT MATTERS
The new design could lead to inexpensive solar power that keeps working after the sun sets.

KEY PLAYERS
- David Bierman, Marin Soljacic, and Evelyn Wang, MIT
- Vladimir Shalaev, Purdue University

AVAILABILITY
10 to 15 years

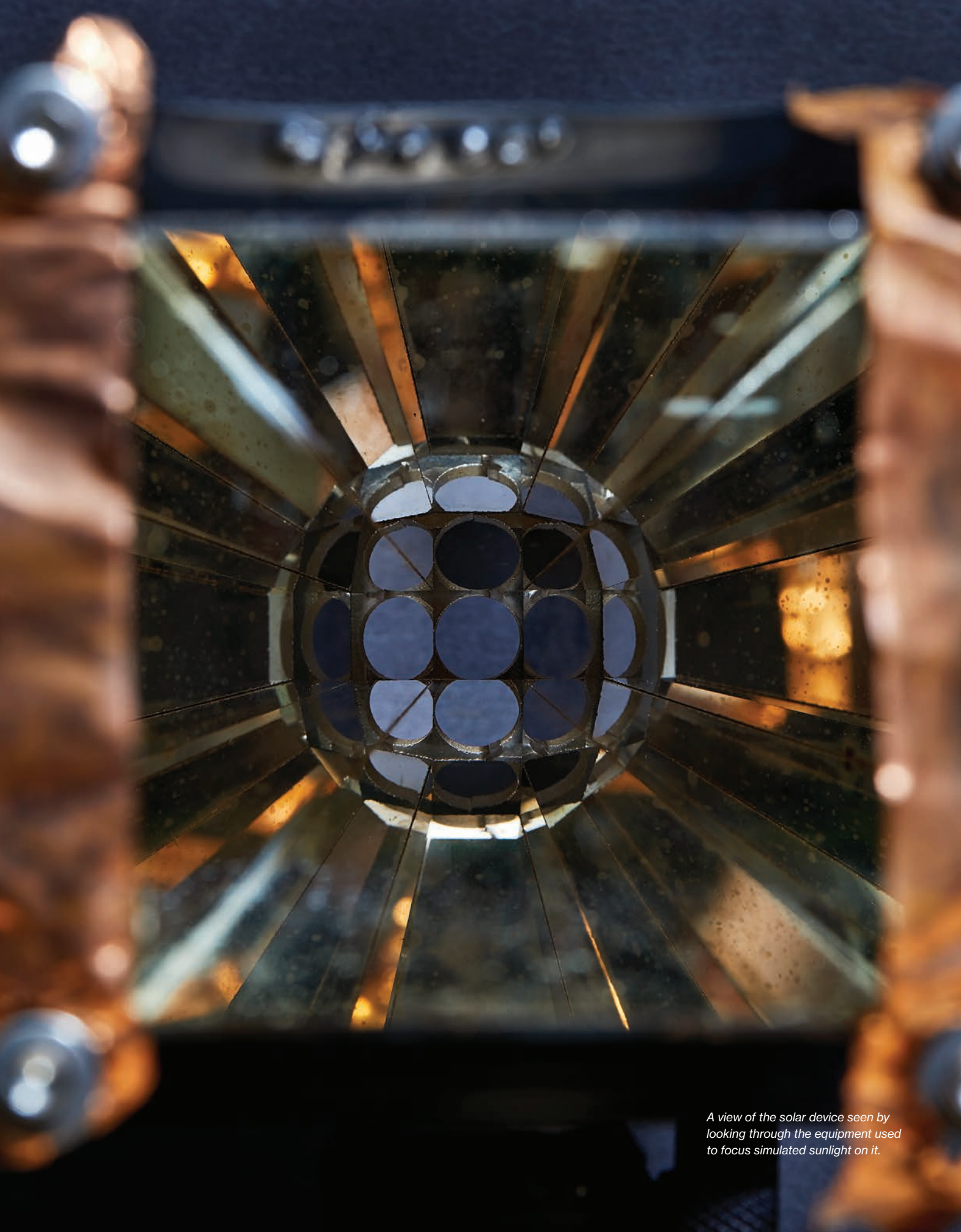
By converting heat to focused beams of light, a new solar device could create cheap and continuous power.

By JAMES TEMPLE

Solar panels cover a growing number of rooftops, but even decades after they were first developed, the slabs of silicon remain bulky, expensive, and inefficient. Fundamental limitations prevent these conventional photovoltaics from absorbing more than a fraction of the energy in sunlight.

But a team of MIT scientists has built a different sort of solar energy device that uses inventive engineering and advances in materials science to capture far more of the sun's energy. The trick is to first turn sunlight into heat and then convert it back into light, but now focused within the spectrum that solar cells can use. While various researchers have been working for years on

PHOTOGRAPHY BY KEN RICHARDSON



A view of the solar device seen by looking through the equipment used to focus simulated sunlight on it.

so-called solar thermophotovoltaics, the MIT device is the first one to absorb more energy than its photovoltaic cell alone, demonstrating that the approach could dramatically increase efficiency.

Standard silicon solar cells mainly capture the visual light from violet to red. That and other factors mean that they can never turn more than around 32 percent of the energy in sunlight into electricity. The MIT device is still a crude prototype, operating at just 6.8 percent efficiency—but with various enhancements it could be roughly twice as efficient as conventional photovoltaics.

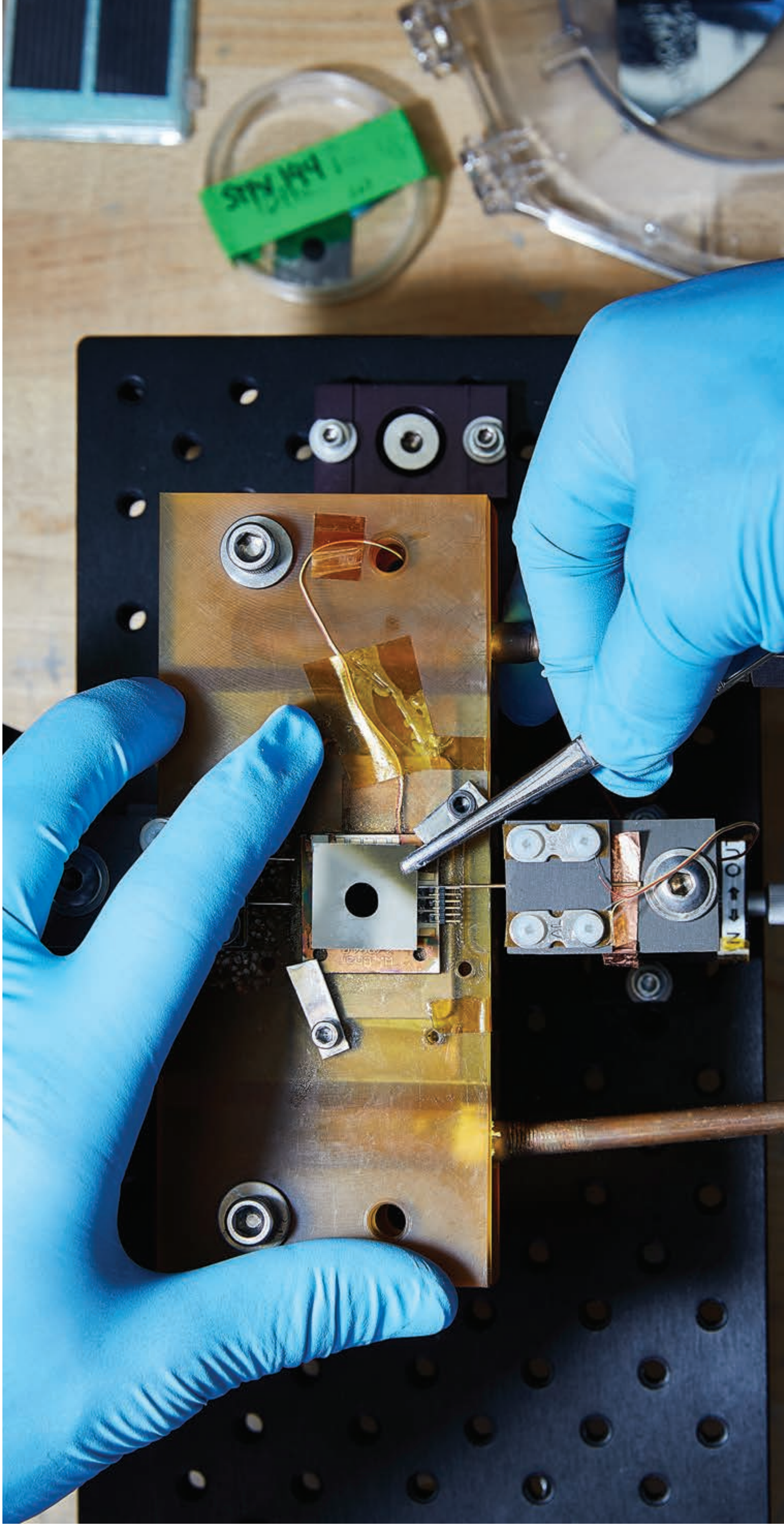
The key step in creating the device was the development of something called an absorber-emitter. It essentially acts as a light funnel above the solar cells. The absorbing layer is built from solid black carbon nanotubes that capture all the energy in sunlight and convert most of it into heat. As temperatures reach around 1,000 °C, the adjacent emitting layer radiates that energy back out as light, now mostly narrowed to bands that the photovoltaic cells can absorb. The emitter is made from a photonic crystal, a structure that can be designed at the nanoscale to control which wavelengths of light flow through it. Another critical advance was the addition of a highly specialized optical filter that transmits the tailored light while reflecting nearly all the unusable photons back. This "photon recycling" produces more heat, which generates more of the light that the solar cell can absorb, improving the efficiency of the system.

There are some downsides to the MIT team's approach, including the relatively high cost of certain components. It also currently works only in a vacuum. But the economics should improve as efficiency levels climb, and the researchers now have

Above: Black carbon nanotubes sit on top of the absorber-emitter layer, collecting energy across the solar spectrum and converting it to heat.

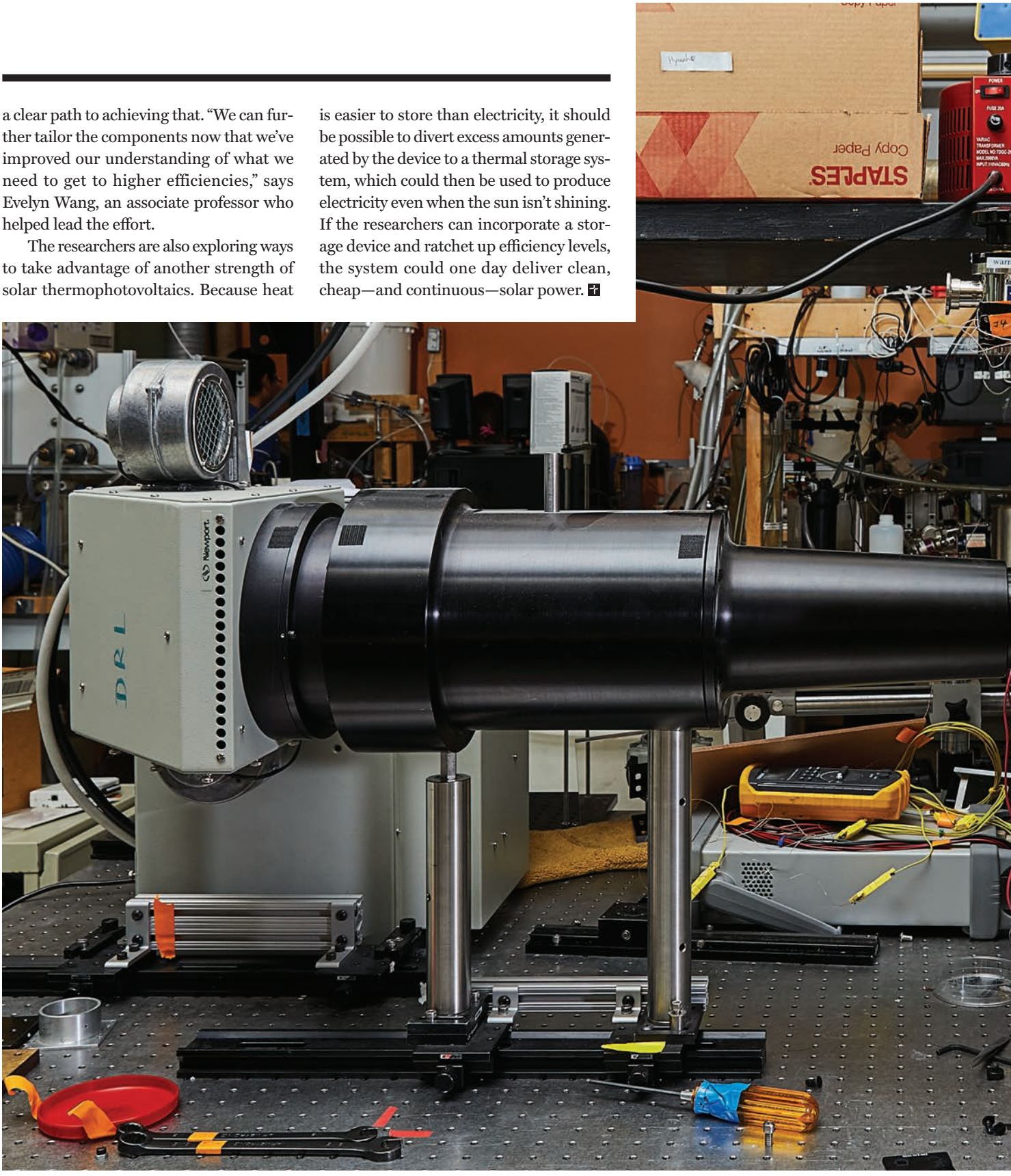
Facing page: The absorber-emitter layer is situated above an optical filter and photovoltaic cell, which is visible underneath.

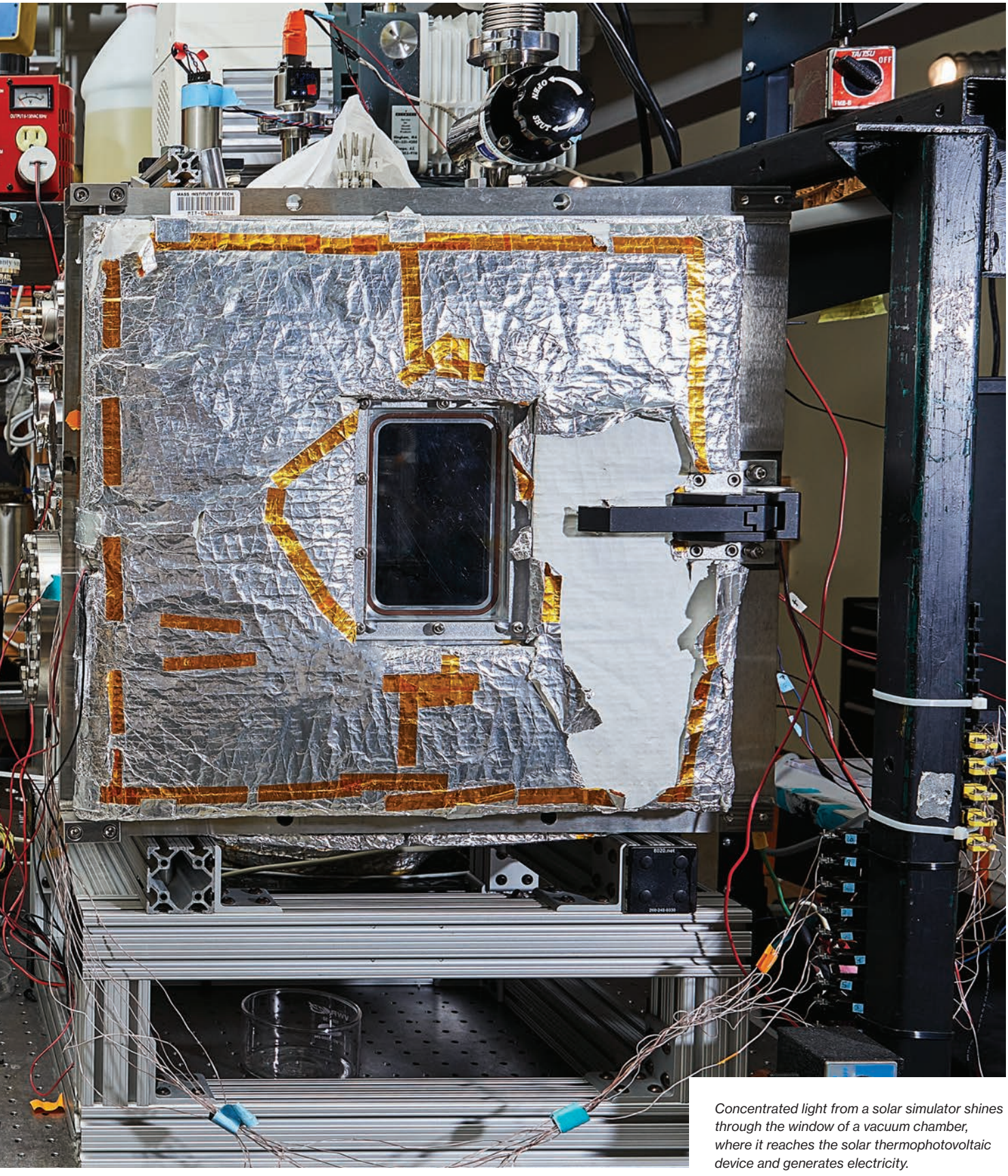
The device eventually could be twice as
EFFICIENT AS CONVENTIONAL PHOTOVOLTAICS.



a clear path to achieving that. "We can further tailor the components now that we've improved our understanding of what we need to get to higher efficiencies," says Evelyn Wang, an associate professor who helped lead the effort.

The researchers are also exploring ways to take advantage of another strength of solar thermophotovoltaics. Because heat is easier to store than electricity, it should be possible to divert excess amounts generated by the device to a thermal storage system, which could then be used to produce electricity even when the sun isn't shining. If the researchers can incorporate a storage device and ratchet up efficiency levels, the system could one day deliver clean, cheap—and continuous—solar power.





Concentrated light from a solar simulator shines through the window of a vacuum chamber, where it reaches the solar thermophotovoltaic device and generates electricity.

MIT TECHNOLOGY REVIEW
VOL. 120 | NO. 2

BREAKTHROUGH
A master catalog of every cell type in the human body.

WHY IT MATTERS
Super-accurate models of human physiology will speed up the discovery and testing of new drugs.

KEY PLAYERS
- Broad Institute
- Sanger Institute
- Chan Zuckerberg Biohub

AVAILABILITY
5 years

The CELL Atlas

Biology's next mega-project will find out what we're really made of.

By **STEVE CONNOR**

FRED TOMASELLI
Airborne Event
2003
Mixed media, acrylic paint, resin on wood

In 1665, Robert Hooke peered down his microscope at a piece of cork and discovered little boxes that reminded him of rooms in a monastery. Being the first scientist to describe cells, Hooke would be amazed by biology's next mega-project: a scheme to individually capture and scrutinize millions of cells using the most powerful tools in modern genomics and cell biology.

The objective is to construct the first comprehensive "cell atlas," or map of human cells, a technological marvel that should comprehensively reveal, for the first time, what human bodies are actually made of and provide scientists a sophisticated new model of biology that could speed the search for drugs.

To perform the task of cataloguing the 37.2 trillion cells of the human body, an international consortium of scientists from the U.S., U.K., Sweden, Israel, the Netherlands, and Japan is being assembled to assign each a molecular signature and also give each type a zip code in the three-dimensional space of our bodies.

"We will see some things that we expect, things we know to exist, but I'm sure there will be completely novel things," says Mike Stubbington, head of the cell atlas team at the Sanger Institute in the U.K. "I think there will be surprises."

Previous attempts at describing cells, from the hairy neurons that populate the brain and spinal cord to the glutinous fat cells of the skin, suggest there are about 300 variations in total. But the true figure is undoubtedly larger. Analyzing molecular differences between cells has already revealed, for example, two new types of retinal cells that escaped decades of investigation of the eye; a cell that forms the first line of defense against pathogens and makes up four in every 10,000 blood cells; and a newly spotted immune cell that uniquely produces a steroid that appears to suppress the immune response.

Scientists are building an ultra-detailed "human cell atlas" that defines living cells by what GOES ON INSIDE THEM.

Fig. 1 *Robert Hooke's drawing of cork, as seen through a microscope (1665).*

Fig. 2 *Sperm containing a homunculus (Nicholas Hartsoeker, 1695).*

Fig. 3 *Daguerreotypes of blood from humans, camels, and toads (A. Donné, 1845).*

Fig. 4 *Plant cells (J. M. Schleiden, 1838).*

Fig. 5 *Sketches of animal cells (Theodor Schwann, 1839).*

Fig. 6 *A nerve (A. von Kolliker, 1852).*

Three technologies are coming together to make this new type of mapping possible. The first is known as "cellular microfluidics." Individual cells are separated, tagged with tiny beads, and manipulated in droplets of oil that are shunted like cars down the narrow, one-way streets of artificial capillaries etched into a tiny chip, so they can be corralled, cracked open, and studied one by one.

The second is the ability to identify the genes active in single cells by decoding them in superfast and efficient sequencing machines at a cost of just a few cents per cell. One scientist can now process 10,000 cells in a single day.

The third technology uses novel labeling and staining techniques that can locate each type of cell—on the basis of its gene activity—at a specific zip code in a human organ or tissue.

Behind the cell atlas are big-science powerhouses including Britain's Sanger Institute, the Broad Institute of MIT and Harvard, and a new "Biohub" in California funded by Facebook CEO Mark Zuckerberg. In September Zuckerberg and his wife, Priscilla Chan, made the cell atlas the inaugural target of a $3 billion donation to medical research.

FIG. 1

FIG. 2

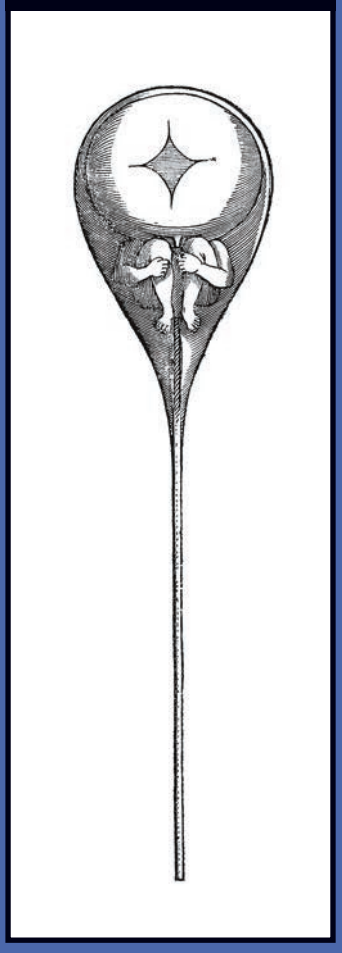


FIG. 3

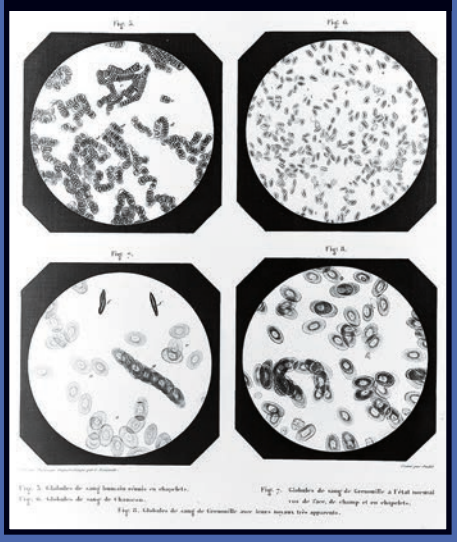


FIG. 5

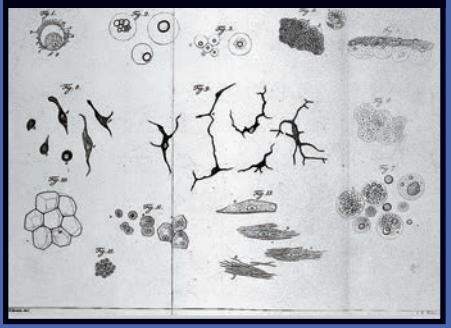


FIG. 4

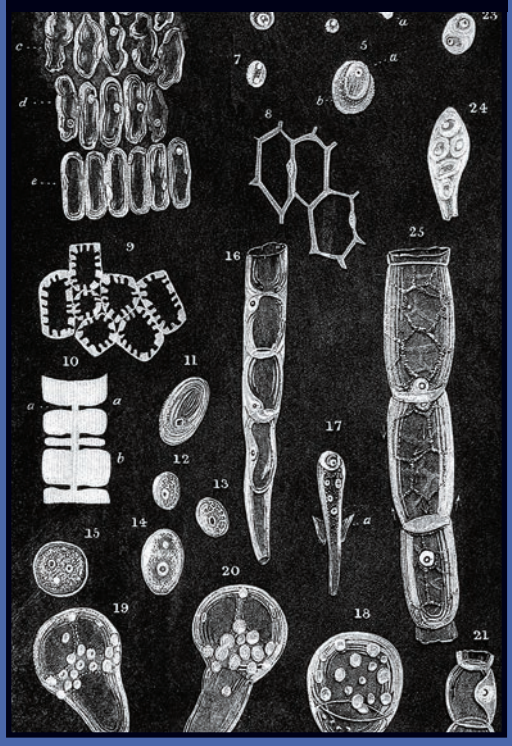
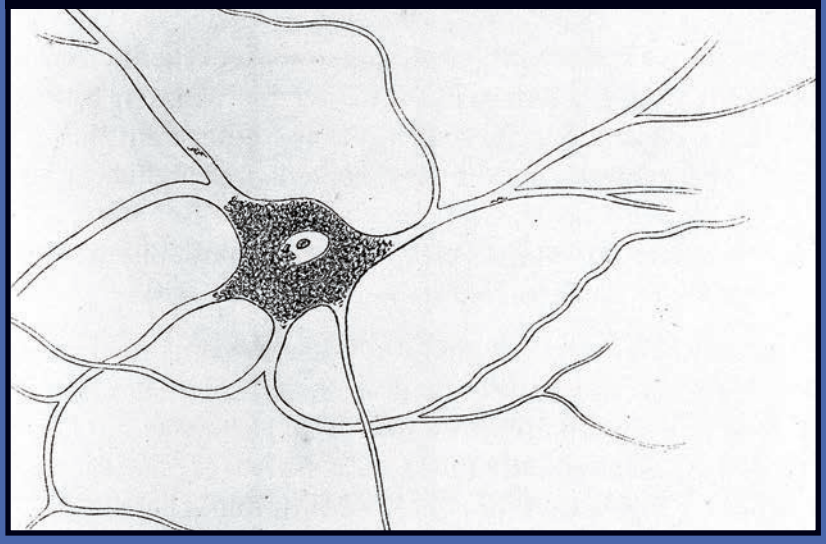


FIG. 6



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SELF-DRIVING
Trucks

BREAKTHROUGH
Long-haul trucks that drive themselves for extended stretches on highways.

WHY IT MATTERS
The technology might free truck drivers to complete routes more efficiently, but it could also erode their pay and eventually replace many of them altogether.

KEY PLAYERS
- Otto
- Volvo
- Daimler
- Peterbilt

AVAILABILITY
5 to 10 years

Tractor-trailers without a human at the wheel will soon barrel onto highways near you. What will this mean for the nation's 1.7 million truck drivers?

By DAVID H. FREEDMAN

Roman Mugriyev was driving his long-haul 18-wheeler down a two-lane Texas highway when he saw an oncoming car drift into his lane just a few hundred feet ahead. There was a ditch to his right and more oncoming cars to his left, so there was little for him to do but hit his horn and brake. "I could hear the man who taught me to drive telling me what he always said was rule number one: 'Don't hurt anybody,'" Mugriyev recalls.

But it wasn't going to work out that way. The errant car collided with the front of Mugriyev's truck. It shattered his front axle, and he struggled to keep his truck and the wrecked car now fused to it from hitting anyone else as it barreled down the road. After Mugriyev finally came to a stop, he learned that the woman driving the car had been killed in the collision.

Could a computer have done better at the wheel? Or would it have done worse?

We will probably find out in the next few years, because multiple companies are now testing self-driving trucks. Although many technical problems are still unresolved, proponents claim that self-driving trucks will be safer and less costly. "This system often drives better than I do," says Greg Murphy, who's been a professional truck driver for 40 years. He now serves as a safety backup driver during tests of self-driving trucks by Otto, a San Francisco company that outfits trucks with the equipment needed to drive themselves.

At first glance, the opportunities and challenges posed by self-driving trucks might seem to merely echo those associated with self-driving cars. But trucks aren't just long cars. For one thing, the economic rationale for self-driving trucks might be even stronger than the one for driverless cars. Autonomous trucks can coördinate their movements to platoon closely together over long stretches of highway, cutting down on wind drag and saving on fuel. And letting the truck drive itself part of the time figures to help truckers complete their routes sooner.

But the technological obstacles facing autonomous trucks are higher than the ones for self-driving cars. Otto and other companies will need to demonstrate that sensors and code can match the situational awareness of a professional trucker—skills honed by years of experience and training in piloting an easily destabilized juggernaut, with the momentum of 25 Honda Accords, in the face of confusing road hazards, poor surface conditions, and unpredictable car drivers.

And perhaps most important, if self-driving trucks do take hold, they figure to be more controversial than self-driving cars. At a time when our politics and economy are already being upended by the threats that automation poses to jobs (see "The Relentless Pace of Automation," page 92), self-driving trucks will affect an enormous number of blue-collar workers. There are 1.7 million trucking jobs in the U.S., according to the Bureau of Labor Statistics. Technology is unlikely to replace truckers entirely anytime soon. But it will almost certainly alter the nature of the job, and not necessarily in ways that all would welcome.

ANDREW PAYNTER; COURTESY OF OTTO

"WE'RE NOT WAITING"

Otto's headquarters, in the once-seedy South of Market section of San Francisco, isn't much like many of the other tech startups that have transformed the area. Proudly oblivious to that neighborhood upgrade, it's a barely renovated former furniture warehouse converted to a garage and machine shop, with semi trucks in various states of dismantlement hulking over benches of tools and computers. "No fancy, shiny offices here," brags Eric Berdinis, Otto's young and clean-cut-looking product manager.

Berdinis shows off the latest generation of the company's fast-evolving technology, which is currently installed on Volvo semis. Unlike the bolted-on, kludgy-looking hardware that's been on testing runs for the past year, the newer versions of the company's sensor and processing arrays are more sleekly integrated throughout the Volvo cab. The equipment includes four forward-facing video cameras, radar, and a box of accelerometers that Berdinis boasts is "as close as the government allows you to get to missile-guidance quality."

Particularly key to Otto's technology is a lidar system, which uses a pulsed laser to amass detailed data about the truck's surroundings. The current third-party lidar box costs Otto in the vicinity of $100,000 each. But the company has a team designing a proprietary version that could cost less than $10,000.

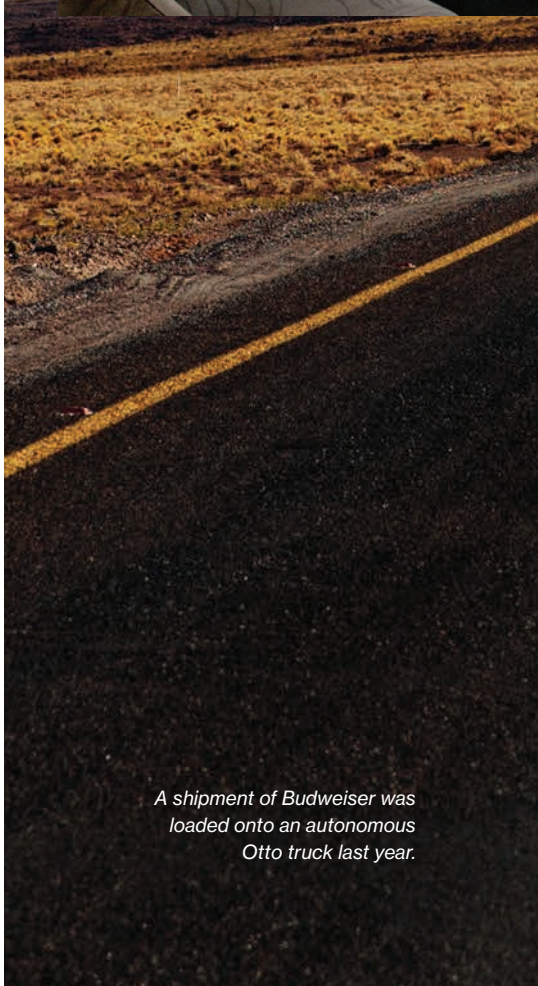
Inside the cab is a custom-built, liquid-cooled, breadbox-size microsupercomputer that, Berdinis claims, provides the most computing muscle ever crammed into so small a package. It is needed to crunch the vast stream of sensor data and shepherd it through the guidance algorithms that adjust braking and steering commands to compensate for the truck's load weight. Rounding out the hardware lineup is a drive-by-wire box to turn the computer's output into physical truck-control signals. It does this through electromechanical actuators mounted to the truck's mechanical steering, throttling, and braking systems. Two big red buttons in the cab—Otto calls them the Big Red Buttons—can cut off all self-driving activity. But even without them, the system is designed to yield to any urgent tugs on the steering wheel or heavy pumps of the pedals from anyone in the driver's seat.

Otto was founded early in 2016 by Anthony Levandowski, who had been with Google's self-driving-car effort, and Lior Ron, who headed up Google Maps, along with two others. It was a natural move to build on Google's vast experience with its autonomous cars, which have driven more than two million miles on U.S. roads in several states, with an eye toward the four million trucks in the U.S. alone. Volvo Trucks, Daimler Trucks, and Peterbilt have been working on their own autonomous-truck technology.

Then, as further validation, Uber snatched Otto up for a reported $680 million last August. That deal has given Otto's team access to roughly 500 engineers at Uber working on self-driving technology, according to Berdinis. Levandowski now heads that effort for Uber, which has said it envisions providing an overarching and largely automated transportation network for both goods and people.

Otto has only seven trucks on the road with its technology, but it hopes owners of many more trucks will eventually take on the equipment for free to test it out. Berdinis says the company is working to drive down the cost of the technology to the point where it offers a one- or two-year payback. That's likely to mean something in the vicinity of $30,000 for a retrofit. "We expect the government to mandate this technology eventually, and for truck manufacturers to integrate it into their vehicles," says Berdinis. "But new-truck development is on an eight-year cycle, and we're not waiting."

A human can push the red buttons to the right of the steering wheel to instantly take over from the self-driving system.



A shipment of Budweiser was loaded onto an autonomous Otto truck last year.

The driver can sit in the back of the cab while the truck drives itself—albeit in the right lane only.

Greg Murphy, a longtime long-haul trucker, keeps an eye on things during tests of Otto trucks.

Roman Mugriyev wonders how well self-driving trucks would handle dangerous situations.

PAY CUTS

Last October an Otto-outfitted self-driving truck carried 2,000 cases of Budweiser beer 200 kilometers down Interstate 25 in Colorado from Fort Collins to Colorado Springs—while the truck's only human driver sat in the sleeper berth at the back of the cab without touching the vehicle's controls.

That commercial delivery, the first ever to be handled by an autonomous heavy truck, illustrated the potential of the technology. But it also demonstrated the current limitations. The human driver piloted the truck to and from the highway the old-fashioned way, because the technology doesn't drive on small rural roads or in cities. Even after it was on the highway, a car drove ahead of the truck to make sure the far right lane remained clear. Otto's system is programmed to stay in that lane, because on many roads trucks are restricted to the far right and are generally considered safer there. And the truck was surrounded by several cars carrying Otto personnel and Colorado State Patrol staff.

In all other testing of Otto-equipped trucks, a professional driver like Greg Murphy sits in the driver's seat, constantly ready to take the controls at a moment's notice, even on the highway. Another Otto employee is in the cab as well. Murphy hits the Big Red Buttons when there's debris on the road, or construction. "My hands are always on the wheel, and I have to concentrate pretty hard to be ready," says Murphy. "It's actually harder than normal driving." (I was invited to sit in on an Otto test ride, but shortly before I was due to show up I was told there had been a scheduling miscommunication and a truck wouldn't be available. I suspect the cancellation had more to do with that morning's heavy rain—which can throw off autonomous vehicles—but Otto stuck to its story.)

In fact, Otto insists it has no plans to release products intended to operate trucks without a driver in the cab. "We're at least a decade away from having trucks with no driver in it," says Berdinis. But Otto does expect to free up the driver during highway cruising to remain in the back of the cab relaxing, working, or even napping. And therein lies the strongest part of the economic case for self-driving trucks. Drivers are legally restricted to 11 hours of driving a day and 60 hours a week. Given that a new big rig goes for about $150,000, and taking into account the vast delays that pulling over to rest injects into the movement of goods, trucks that can cruise nearly 24/7 could dramatically lower freight costs.

Even if drivers stay on in the cab, it's not clear THE ECONOMICS WILL WORK OUT IN THEIR FAVOR.

There are other anticipated savings from having trucks drive themselves across America's 230,000 miles of highway. Fuel is about a third of the cost of operating a long-haul truck, and while drivers are capable of wringing maximum miles per gallon from their trucks, many are too heavy-footed on the pedals. (Berdinis says the best drivers are 30 percent more fuel-efficient than the worst ones.) Otto's equipment is programmed to keep trucks pegged to optimal speeds and acceleration.

Then there's the potential to cut down on accidents. Truck and bus crashes kill about 4,000 people a year in the U.S. and injure another 100,000. Driver fatigue is a factor in roughly one of seven fatal truck accidents. More than 90 percent of all accidents are caused at least in part by some form of driver error. We don't yet know what fraction of those errors would be eliminated by autonomous technology—or what new errors might be introduced by it—but tests of self-driving cars suggest the technology will cut down on mistakes.

As long as self-driving trucks require a driver to remain on board, driving jobs seem safe. In some ways those jobs, which pay an average of about $40,000 a year, could even improve. For one thing, driving a truck 11 hours a day is stressful. "You get physically and mentally tired," says Mugriyev, the driver in the Texas accident, which occurred in 2013. (He was not found to be at fault.) Besides being able

Otto says it has no intention of getting drivers out of the cab entirely—at least for the next decade.

A key detail not seen in most images of the Budweiser delivery: Otto staff and police riding nearby in cars to ensure safety. Inset: Otto's facility in San Francisco.

to nap and relax in the cab while Otto does the driving, says Berdinis, drivers could use the time away from the wheel to catch up on trucking's heavy paperwork, locate a "backhaul" load that would pay for the return trip, chat with family and friends, learn a second trade, or run a business. "And while they're doing it, the drivers are still getting paid for driving," he says.

These potential benefits could help with recruiting and training truck drivers—a key concern, because there's actually a big shortage of drivers in both the U.S. and Europe. The American Trucking Associations pegs the current U.S. shortage at about 50,000 drivers and predicts that a total of nearly 900,000 new drivers will be needed over the next eight years. "We have customers calling us up saying they'll buy 10 new trucks from us if we can provide the drivers, too," says Carl Johan Almqvist, who heads product safety at Volvo Trucks.

One endorsement of the potential benefits of autonomous trucks to both trucking companies and drivers has come from the state government of Ohio, a trucking hub that's home to more than 70,000 drivers. The state has committed $15 million to set up a 35-mile stretch of highway outside Columbus for testing self-driving trucks. The heads of both the American Trucking Associations and the Ohio Trucking Association have publicly suggested that autonomous trucks will be good for truckers.

However, the technology is not just a way to make the job more attractive to human drivers; it's potentially a way for trucking companies to fill in for drivers who aren't available. And if self-driving systems someday become accepted as capable of standing in for drivers, why keep human drivers on at all? After all, drivers account for a third of the per-mile costs of operating a truck.

Even if, as is likely for the foreseeable future, drivers stay on in the cab of self-driving trucks, it's not clear the economics will work out in their favor. That's because there's currently no regulation that would require companies to pay drivers for the time they spend in the back of the cab. What's more, freight companies are likely to be forced to convert the cost savings from always-rolling trucks into lower hauling charges in order to compete. Those dropping fees could put pressure on truckers' pay. "If load prices get pushed down with this technology, the company will say, 'You didn't do as much driving, so you don't make as much,'" says Mugriyev.

SAFETY QUESTIONS

Is Otto's technology up to safely piloting 80,000 pounds of truck down a busy highway? Having a driver in the cab won't do much to make up for any shortcomings

in the system, given that by Otto's own reckoning it can take up to 30 seconds for a driver resting in the back to fully orient to the driver's seat.

The extensive history racked up by Google's self-driving cars is encouraging, with only 20 crashes over seven years and millions of miles. Only one of the crashes was found to be the fault of the car: a traffic merging situation of the sort that Otto hands off to the driver.

But that record doesn't easily translate into a prediction for the safety of self-driving trucks. As Berdinis notes, trucks can't swerve to avoid a hazard the way cars can. A fast, hard turn of the steering wheel at high speed would set the truck to fishtailing and possibly jackknifing. From the moment the brakes are applied in a truck going 55 miles per hour, it takes well over the length of a football field for the vehicle to stop. There are only six inches of lane on either side of a truck, meaning even small hazards at the side of the lane can't be avoided without leaving the lane. "Many avoidance algorithms for self-driving cars just don't apply to trucks," says Berdinis.

One advantage for trucks is that some of the sensors can be mounted at the top of the cab, providing a high-up view that can see over traffic far ahead. But even state-of-the-art sensors can struggle to provide accurate, unambiguous data. Bright sunlight can briefly blind cameras, computers can't always differentiate between a car by the side of the road and a big sign, and systems can be thrown off by snow, ice, and sand. They also can't interpret facial expressions and gestures of nearby drivers to predict the driving behavior of other vehicles. And few systems would be able to differentiate between a hitchhiker and a construction worker gesturing to pull over.

Self-driving cars have managed to do well in mostly city driving in spite of these limitations, but at highway speeds and with limited maneuverability, trucks may come up short more often. "We're still having problems with these challenges," says Volvo Trucks' Almqvist. Heavy-truck drivers typically spend months in driving school, and go through thousands of miles of supervised driving, before taking full charge of a big rig. Thus, matching a human driver's skill is harder for a self-driving truck than it is for a self-driving car. Mugriyev wonders, for example, if an autonomous system would be able to do what he did: wrestle to a safe stop a truck with a blown front axle and a smashed-up car pasted to its front.

Because of such safety concerns, Volvo has no current plans to field its autonomous trucks on public roads. Instead, it intends to limit them to private locations such as mines and ports. "On public roads, we'll use the technology to support the driver, not to replace the driver," says Almqvist. Volvo is still unsure about social acceptance of the technology. The company sometimes identifies the license plates of passing cars when testing its autonomous trucks, and then tracks the car owners down and surveys them about their perceptions.

Berdinis acknowledges the challenges, but he insists Otto's technology is rapidly evolving to meet them. "We won't ship until we're confident there are no situations where we'd need a human to immediately take control of the truck," he says.

Otto will also have to convince regulators its systems are ready for the highway. Unlike Uber, which has relied on the consumer popularity of its passenger service to take to the roads first and wrestle with regulations later, Otto will do everything strictly by the book, notes Berdinis.

Even Volvo's Almqvist thinks the technology will make it to public roads in the not-too-distant future. But timing will be crucial, he adds: "If we do it too soon and have an accident, we'll hurt the industry. And if you lose the public's trust, it's very difficult to regain it."

BREAKTHROUGH
Face recognition technology that is finally accurate enough to be widely used in financial transactions and other everyday applications.

WHY IT MATTERS
The technology offers a secure and extremely convenient method of payment but could raise privacy concerns.

KEY PLAYERS
- Face++
- Baidu
- Alibaba

AVAILABILITY
Now

Paying with YOUR FACE

Face-detecting systems in China now authorize payments, provide access to facilities, and track down criminals. Will other countries follow?

By **WILL KNIGHT**

YOSHI SODEOKA

Shortly after walking through the door at Face++, a Chinese startup valued at roughly a billion dollars, I see my face, unshaven and looking a bit jet-lagged, flash up on a large screen near the entrance.

Having been added to a database, my face now provides automatic access to the building. It can also be used to monitor my movements through each room inside. As I tour the offices of Face++ (pronounced "face plus plus"), located in a suburb of Beijing, I see it appear on several more screens, automatically captured from countless angles by the company's software. On one screen a video shows the software tracking 83 different points on my face simultaneously. It's a little creepy, but undeniably impressive.

Over the past few years, computers have become incredibly good at recognizing faces, and the technology is expanding quickly in China in the interest of both surveillance and convenience. Face recognition might transform everything from policing to the way people interact every day with banks, stores, and transportation services.

Technology from Face++ is already being used in several popular apps. It is possible to transfer money through Alipay, a mobile payment app used by more than 120 million people in China, using only your face as credentials. Meanwhile, Didi, China's dominant ride-hailing company, uses the Face++ software to let passengers confirm that the person behind the wheel is a legitimate driver. (A "liveness" test, designed to prevent anyone from duping the system with a photo, requires people being scanned to move their head or speak while the app scans them.)

The technology figures to take off in China first because of the country's attitudes toward surveillance and privacy. Unlike, say, the United States, China has a large centralized database of ID card photos. During my time at Face++, I saw how local governments are using its software to identify suspected criminals in video from surveillance cameras, which are omnipresent in the country. This is especially impressive—albeit somewhat dystopian—because the footage analyzed is far from perfect, and because mug shots or other images on file may be several years old.

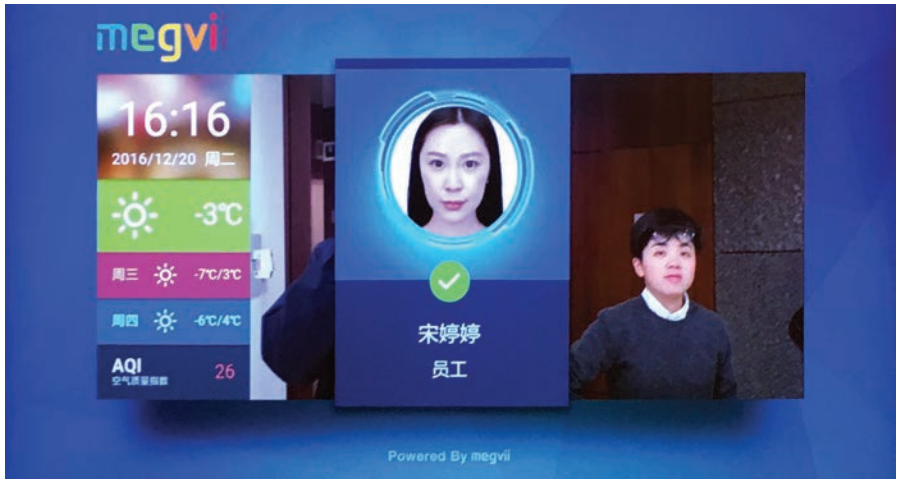
Facial recognition has existed for decades, but only now is it accurate enough to be used in secure financial transactions. The new versions use deep learning, an artificial-intelligence technique that is especially effective for image recognition because it makes a computer zero in on the facial features that will most reliably identify a person (see "10 Breakthrough Technologies 2013: Deep Learning").

"The face recognition market is huge," says Shiliang Zhang, an assistant professor at Peking University who specializes in machine learning and image processing. Zhang heads a lab not far from the offices of Face++. When I arrived, his students were working away furiously in a dozen or so cubicles. "In China security is very important, and we also have lots of people," he says. "Lots of companies are working on it."

One such company is Baidu, which operates China's most popular search engine, along with other services. Baidu researchers have published papers showing that their software rivals most humans in its ability to recognize a face. In January, the company proved this by taking

Face++ pinpoints 83 points on a face. The distance between them provides a means of identification.

COURTESY OF FACE++



Employees simply show their face to gain entry to the company's headquarters.

The system captured MIT Technology Review's *Will Knight as he moved through Face++'s offices.*

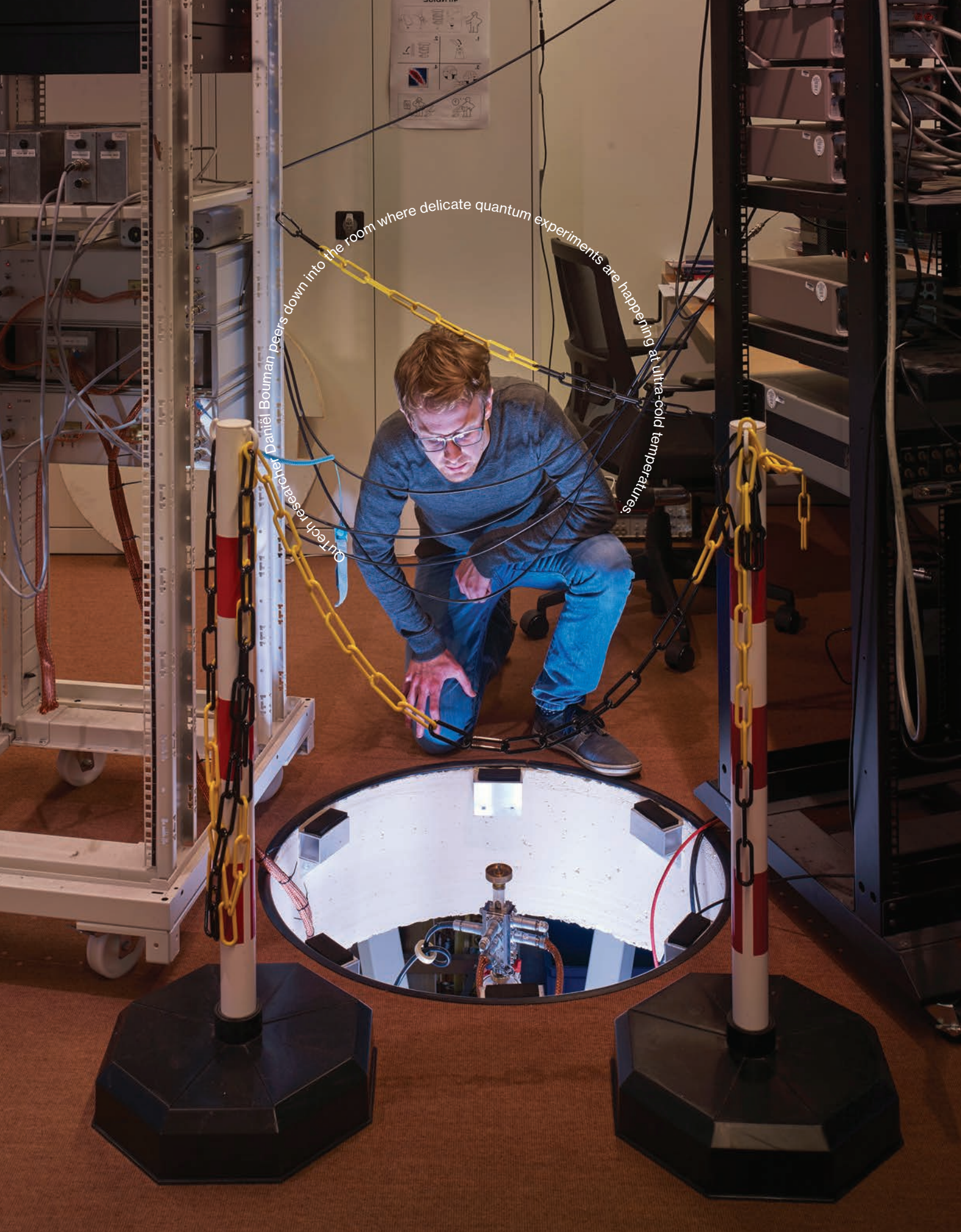
COURTESY OF FACE++; WILL KNIGHT

part in a TV show featuring people who are remarkably good at identifying adults from their baby photos. Baidu's system outshined them.

Now Baidu is developing a system that lets people pick up rail tickets by showing their face. The company is already working with the government of Wuzhen, a historic tourist destination, to provide access to many of its attractions without a ticket. This involves scanning millions of faces in a database to find a match, which Baidu says it can do with 99 percent accuracy.

Jie Tang, an associate professor at Tsinghua University who advised the founders of Face++ as students, says the convenience of the technology is what appeals most to people in China. Some apartment complexes use facial recognition to provide access, and shops and restaurants are looking to the technology to make the customer experience smoother. Not only can he pay for things this way, he says, but the staff in some coffee shops are now alerted by a facial recognition system when he walks in: "They say, 'Hello, Mr. Tang.'" ✚

Local governments are using the software to identify suspected criminals in video from surveillance CAMERAS, WHICH ARE OMNIPRESENT IN CHINA.


QuTech researcher Daniël Bouman peers down into the room where delicate quantum experiments are happening at ultra-cold temperatures

BREAKTHROUGH
The fabrication of stable qubits, the basic unit of quantum computers.

WHY IT MATTERS
Quantum computers could be exponentially faster at running artificial-intelligence programs and handling complex simulations and scheduling problems. They could even create uncrackable encryption.

KEY PLAYERS
- QuTech
- Intel
- Microsoft
- Google
- IBM

AVAILABILITY
4 to 5 years

PRACTICAL Quantum Computers

Advances at Google, Intel, and several research groups indicate that computers with previously unimaginable power are finally within reach.

By **RUSS JUSKALIAN**

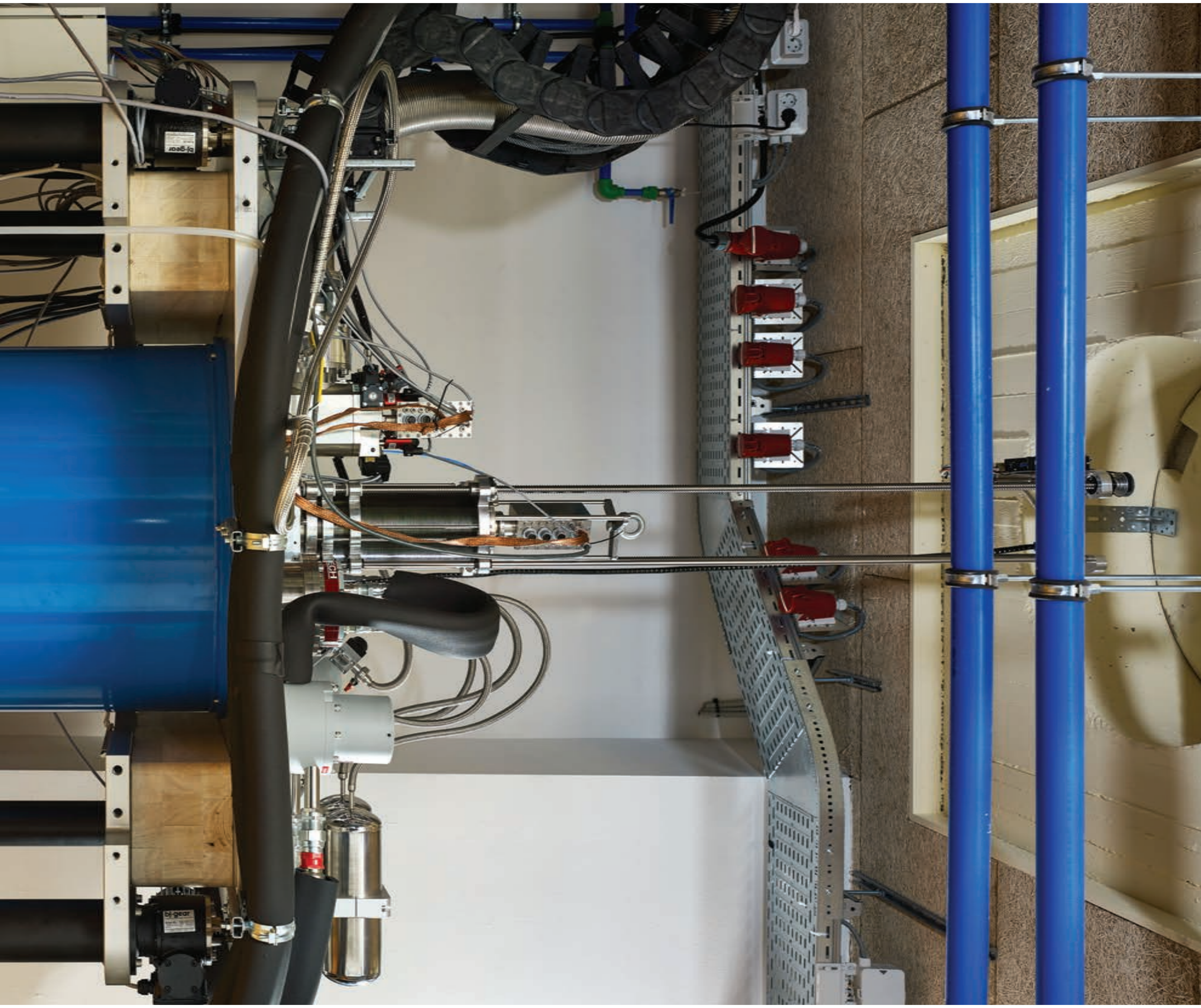
MATTHIJS LABADIE

One of the labs at QuTech, a Dutch research institute, is responsible for some of the world's most advanced work on quantum computing, but it looks like an HVAC testing facility. Tucked away in a quiet corner of the applied sciences building at Delft University of Technology, the space is devoid of people. Buzzing with resonant waves as if occupied by a swarm of electric katydids, it is cluttered by tangles of insulated tubes, wires, and control hardware erupting from big blue cylinders on three and four legs.

Inside the blue cylinders—essentially supercharged refrigerators—spooky quantum-mechanical things are happening where nanowires, semiconductors, and superconductors meet at just a hair above absolute zero. It's here, down at the limits of physics, that solid materials give rise to so-called quasiparticles, whose unusual behavior gives them the potential to serve as the key components of quantum computers. And this lab in particular has taken big steps toward finally bringing those computers to fruition. In a few years they could rewrite encryption, materials science, pharmaceutical research, and artificial intelligence.

Every year quantum computing comes up as a candidate for this Breakthrough Technologies list, and every year we reach the same conclusion: *not yet*. Indeed, for years qubits and quantum computers existed mainly on paper, or in fragile experiments to determine their feasibility. (The Canadian company D-Wave Systems has been selling machines it calls quantum computers for a while, using a specialized technology called quantum annealing. The approach, skeptics say, is at best applicable to a very constrained set of computations and might offer no speed advantage over classical systems.) This year, however, a raft of previously theoretical designs are actually being built. Also new this year is the increased availability of corporate funding—from Google,

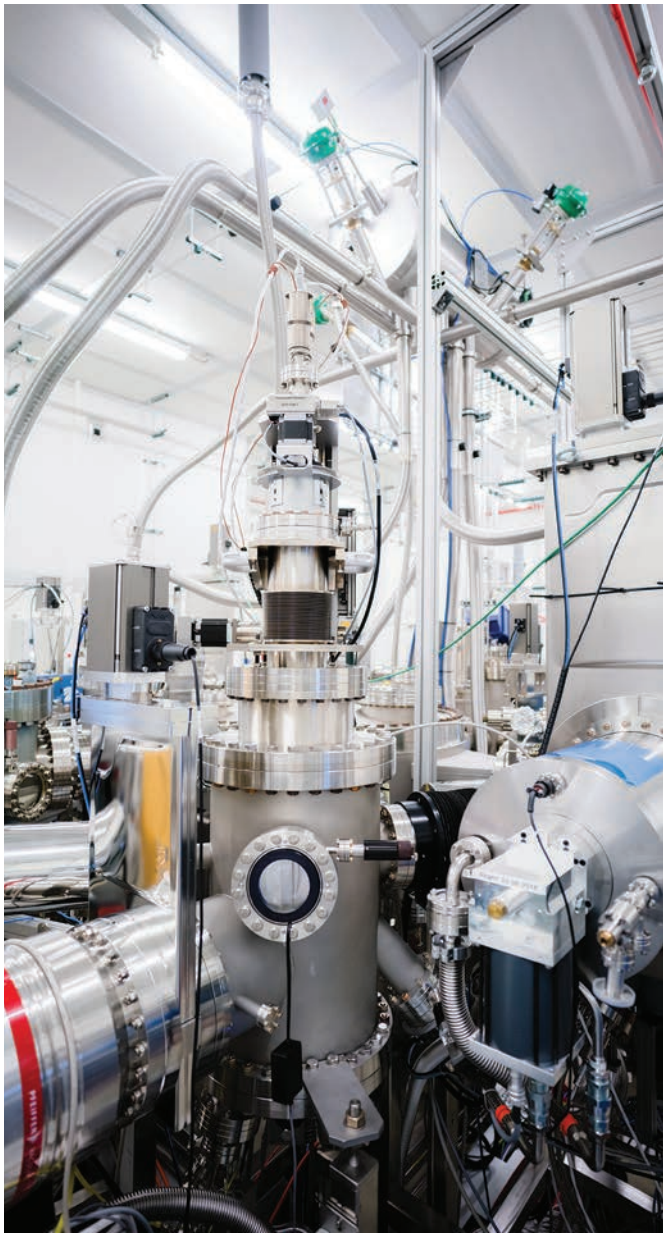
Previously theoretical designs ARE ACTUALLY BEING BUILT.



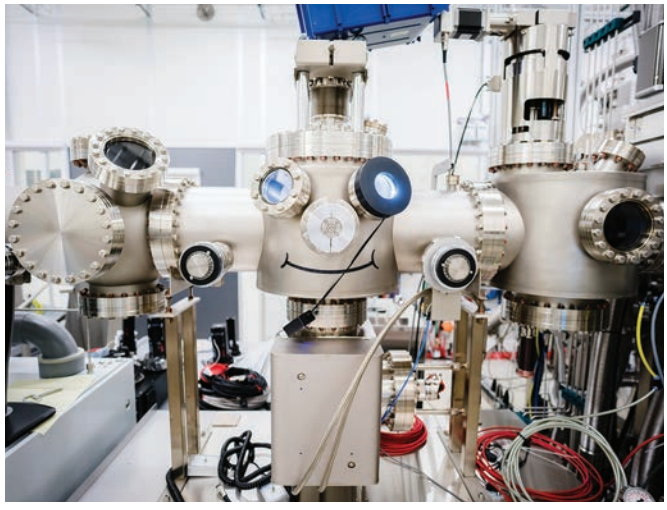
This blue refrigerator gets down to just above absolute zero, making quantum experiments possible on tiny chips deep inside it. On subsequent pages are scenes from the Delft lab where the experiments are prepared.

WHAT IS A QUANTUM COMPUTER?

At the heart of quantum computing is the quantum bit, or qubit, a basic unit of information analogous to the *0*s and *1*s represented by transistors in your computer. Qubits have much more power than classical bits because of two unique properties: they can represent both *1* and *0* at the same time, and they can affect other qubits via a phenomenon known as quantum entanglement. That lets quantum computers take shortcuts to the right answers in certain types of calculations.



RUSS JUSKALIAN



IBM, Intel, and Microsoft, among others—for both research and the development of assorted technologies needed to actually build a working machine: microelectronics, complex circuits, and control software.

The project at Delft, led by Leo Kouwenhoven, a professor who was recently hired by Microsoft, aims to overcome one of the most long-standing obstacles to building quantum computers: the fact that qubits, the basic units of quantum information, are extremely susceptible to noise and therefore error. For qubits to be useful, they must achieve both quantum superposition (a property something like being in two physical states simultaneously) and entanglement (a phenomenon where pairs of qubits are linked so that what happens to one can instantly affect the other, even when they're physically separated). These delicate conditions are easily upset by the slightest disturbance, like vibrations or fluctuating electric fields.

People have long wrestled with this problem in efforts to build quantum computers, which could make it possible to solve problems so complex they exceed the reach of today's best computers. But now Kouwenhoven and his colleagues believe the qubits they are creating could eventually be inherently protected—as stable as knots in a rope. "Despite deforming the rope, pulling on it, whatever," says Kouwenhoven, the knots remain and "you don't change the information." Such stability would allow researchers to scale up quantum computers by substantially reducing the computational power required for error correction.

Kouwenhoven's work relies on manipulating unique quasiparticles that weren't even discovered until 2012. And it's just one of several impressive steps being taken. In the same lab, Lieven Vandersypen, backed by Intel, is showing how quantum circuits can be manufactured on traditional silicon wafers.

Quantum computers will be particularly suited to factoring large numbers (making it easy to crack many of today's encryption techniques and probably providing uncrackable replacements), solving complex optimization problems, and executing machine-learning algorithms. And there will be applications nobody has yet envisioned.

Soon, however, we might have a better idea of what they can do. Until now, researchers have built fully programmable five-qubit computers and more fragile 10- to 20-qubit test systems. Neither kind of machine is capable of much. But the head of Google's quantum computing effort, Harmut Neven, says his team is on target to build a 49-qubit system by as soon as a year from now. The target of around 50 qubits isn't an arbitrary one. It's a threshold, known as quantum supremacy, beyond which no classical supercomputer would be capable of handling the exponential growth in memory and communications bandwidth needed to simulate its quantum counterpart. In other words, the top supercomputer systems can currently do all the same things that five- to 20-qubit quantum computers can, but at around 50 qubits this becomes physically impossible.

All the academic and corporate quantum researchers I spoke with agreed that somewhere between 30 and 100 qubits—particularly qubits stable enough to perform a wide range of computations for longer durations—is where quantum computers start to have commercial value. And as soon as two to five years from now, such systems are likely to be for sale. Eventually, expect 100,000-qubit systems, which will disrupt the materials, chemistry, and drug industries by making accurate molecular-scale models possible for the discovery of new materials and drugs. And a million-physical-qubit system, whose general computing applications are still difficult to even fathom? It's conceivable, says Neven, "on the inside of 10 years."

REVERSING Paralysis

BREAKTHROUGH
Wireless brain-body electronic interfaces to bypass damage to the nervous system.

WHY IT MATTERS
Thousands of people suffer paralyzing injuries every year.

KEY PLAYERS
- École Polytechnique Fédérale de Lausanne
- Wyss Center for Bio and Neuroengineering
- University of Pittsburgh
- Case Western Reserve University

AVAILABILITY
10 to 15 years

Scientists are making remarkable progress at using brain implants to restore the freedom of movement that spinal cord injuries take away.

By ANTONIO REGALADO

"Go, go!" was the thought racing through Grégoire Courtine's mind.

The French neuroscientist was watching a macaque monkey as it hunched aggressively at one end of a treadmill. His team had used a blade to slice halfway through the animal's spinal cord, paralyzing its right leg. Now Courtine wanted to prove he could get the monkey walking again. To do it, he and colleagues had installed a recording device beneath its skull, touching its motor cortex, and sutured a pad of flexible electrodes around the animal's spinal cord, below the injury. A wire-

An implant shown on a silicone model of a primate brain.

ALAIN HERZOG / EPFL

Grégoire Courtine holds the two main parts of the brain-spine interface.

HILLARY SANCTUARY / EPFL

less connection joined the two electronic devices.

The result: a system that read the monkey's intention to move and then transmitted it immediately in the form of bursts of electrical stimulation to its spine. Soon enough, the monkey's right leg began to move. Extend and flex. Extend and flex. It hobbled forward. "The monkey was thinking, and then boom, it was walking," recalls an exultant Courtine, a professor with Switzerland's École Polytechnique Fédérale de Lausanne.

In recent years, lab animals and a few people have controlled computer cursors or robotic arms with their thoughts, thanks to a brain implant wired to machines. Now researchers are taking a significant next step toward reversing paralysis once and for all. They are wirelessly connecting the brain-reading technology directly to electrical stimulators on the body, creating what Courtine calls a "neural bypass" so that people's thoughts can again move their limbs.

At Case Western Reserve University, in Cleveland, a middle-aged quadriplegic—he can't move anything but his head and shoulder—agreed to let doctors place two recording implants in his brain, of the

Top left: A close-up of a brain-reading chip, bristling with electrodes.

Top right: Flexible electrodes developed to simulate the spinal cord.

Above: A model of a wireless neurocommunication device sits on a skull.

ALAIN HERZOG / EPFL; COURTESY OF THE WYSS CENTER

MILESTONES IN NEURAL BYPASS

1961
Physician and inventor William F. House tests the first cochlear implant to restore hearing. The devices will go on to benefit more than 250,000 people.

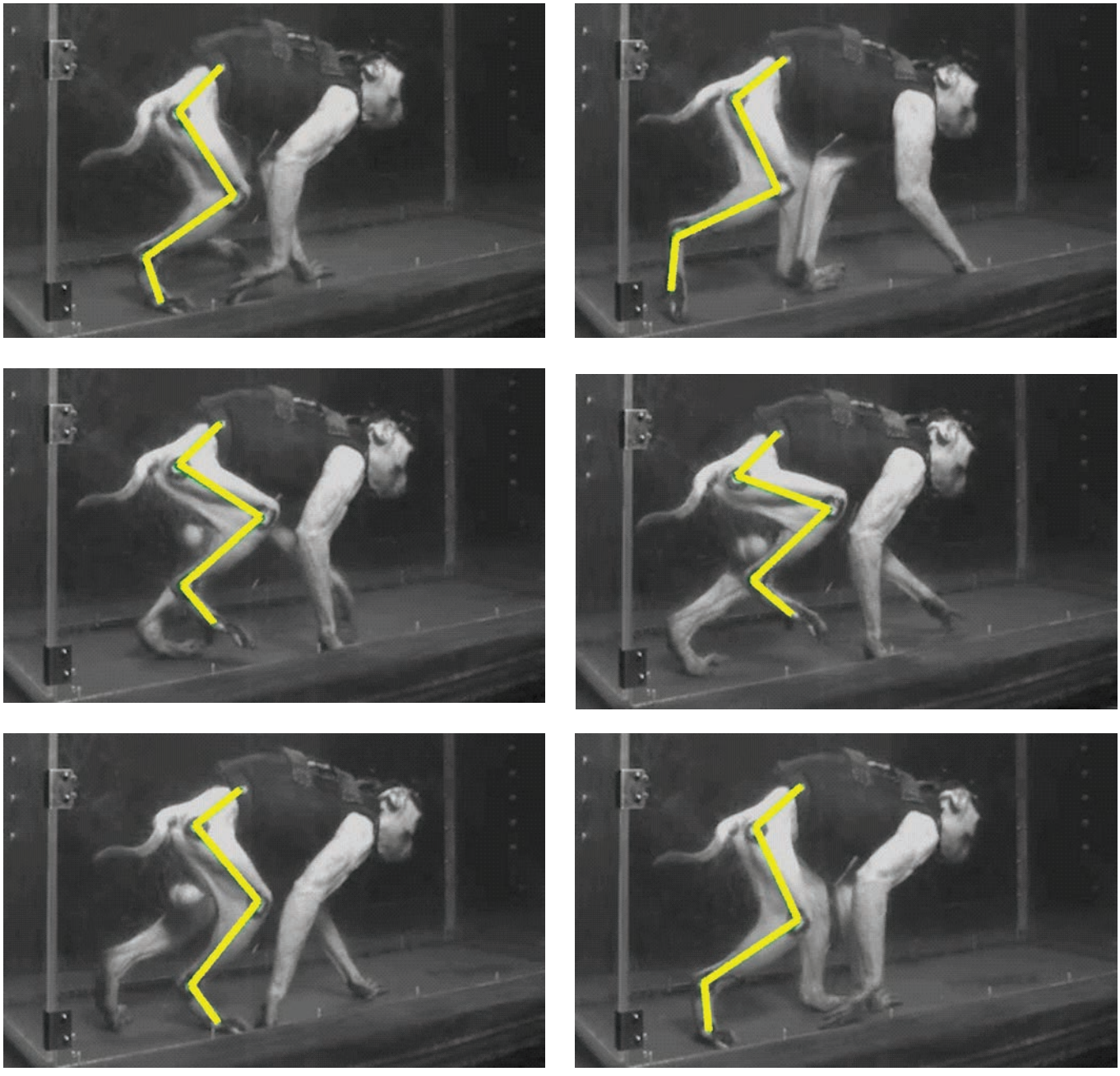
1998
Doctors install a single electrode in the brain of a paralyzed man unable to speak. He uses it to communicate through a computer.

2008
A monkey's brain signals are sent over the Internet from the U.S. to Japan, causing a robot to walk on a treadmill.

2013
U.S. regulators approve a "bionic eye" sold by the company Second Sight. It uses a chip sutured to the retina to bypass injured photoreceptors.

2014-2015
Ohio doctors launch efforts to "reanimate" the arms of two different paralyzed men. The thoughts of each are transmitted to electrodes on their arms, causing their hands to open and shut.

2016
28-year-old Nathan Copeland operates a robotic hand that, via a brain implant, allows him to "feel" the fingers. He fist-bumps Barack Obama during a presidential visit to a lab in Pittsburgh.



In these frames of a video made by EPFL researchers, a monkey with a spinal cord injury that paralyzed its right leg is able to walk again.

EPFL

"People would prefer to be restored to their EVERYDAY SELF. THEY WANT TO BE REANIMATED."

same type Courtine used in the monkeys. Made of silicon, and smaller than a postage stamp, they bristle with a hundred hair-size metal probes that can "listen" as neurons fire off commands.

To complete the bypass, the Case team, led by Robert Kirsch and Bolu Ajiboye, also slid more than 16 fine electrodes into the muscles of the man's arm and hand. In videos of the experiment, the volunteer can be seen slowly raising his arm with the help of a spring-loaded arm rest, and willing his hand to open and close. He even raises a cup with a straw to his lips. Without the system, he can't do any of that.

Just try sitting on your hands for a day. That will give you an idea of the shattering consequences of spinal cord injury. You can't scratch your nose or tousle a child's hair. "But if you have this," says Courtine, reaching for a red espresso cup and raising it to his mouth with an actor's exaggerated motion, "it changes your life."

The Case results, pending publication in a medical journal, are a part of a broader effort to use implanted electronics to restore various senses and abilities. Besides treating paralysis, scientists hope to use so-called neural prosthetics to reverse blindness with chips placed in the eye, and maybe restore memories lost to Alzheimer's disease (see "10 Breakthrough Technologies 2013: Memory Implants").

And they know it could work. Consider cochlear implants, which use a microphone to relay signals directly to the auditory nerve, routing around nonworking parts of the inner ear. Videos of wide-eyed deaf children hearing their mothers for the first time go viral on the Internet every month. More than 250,000 cases of deafness have been treated.

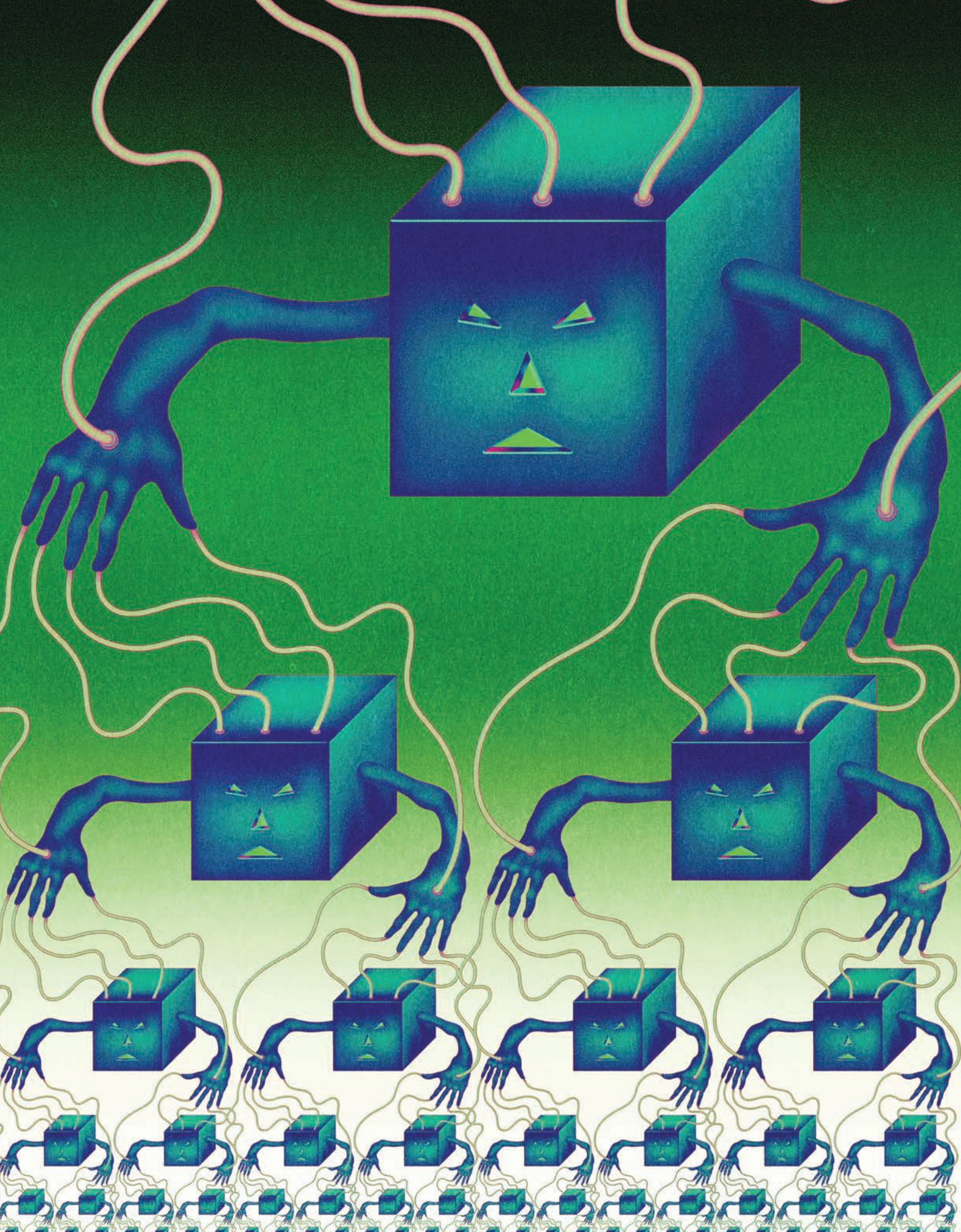
But it's been harder to turn neural prosthetics into something that helps paralyzed people. A patient first used a brain probe to move a computer cursor across a screen back in 1998. That and several other spectacular brain-control feats haven't had any broader practical use. The technology remains too radical and too complex to get out of the lab. "Twenty years of work and nothing in the clinic!" Courtine exclaims, brushing his hair back. "We keep pushing the limits, but it is an important question if this entire field will ever have a product."

Courtine's laboratory is located in a vertiginous glass-and-steel building in Geneva that also houses a $100 million center that the Swiss billionaire Hansjörg Wyss funded specifically to solve the remaining technical obstacles to neurotechnologies like the spinal cord bypass. It's hiring experts from medical-device makers and Swiss watch companies and has outfitted clean rooms where gold wires are printed onto rubbery electrodes that can stretch as our bodies do.

The head of the center is John Donoghue, an American who led the early development of brain implants in the U.S. (see "Implanting Hope," March 2005) and who moved to Geneva two years ago. He is now trying to assemble in one place the enormous technical resources and talent—skilled neuroscientists, technologists, clinicians—needed to create commercially viable systems.

Among Donoghue's top priorities is a "neurocomm," an ultra-compact wireless device that can collect data from the brain at Internet speed. "A radio inside your head," Donoghue calls it, and "the most sophisticated brain communicator in the world." The matchbox-size prototypes are made of biocompatible titanium with a sapphire window. Courtine used an earlier, bulkier version in his monkey tests.

As complex as they are, and as slow as progress has been, neural bypasses are worth pursuing because patients desire them, Donoghue says. "Ask someone if they would like to move their own arm," he says. "People would prefer to be restored to their everyday self. They want to be reanimated."



MIT TECHNOLOGY REVIEW
VOL. 120 | NO. 2

BREAKTHROUGH
Malware that takes control of webcams, video recorders, and other consumer devices to cause widespread Internet outages.

WHY IT MATTERS
Botnets based on this software are disrupting larger and larger swaths of the Internet—and getting harder to stop.

KEY PLAYERS
- Whoever created the Mirai botnet software
- Anyone who runs a poorly secured device online—including you?

AVAILABILITY
Now

BOTNETS of Things

The relentless push to add connectivity to home gadgets is creating dangerous side effects that figure to get even worse.

By **BRUCE SCHNEIER**

ROBERT BEATTY

Botnets have existed for at least a decade. As early as 2000, hackers were breaking into computers over the Internet and controlling them en masse from centralized systems. Among other things, the hackers used the combined computing power of these botnets to launch distributed denial-of-service attacks, which flood websites with traffic to take them down.

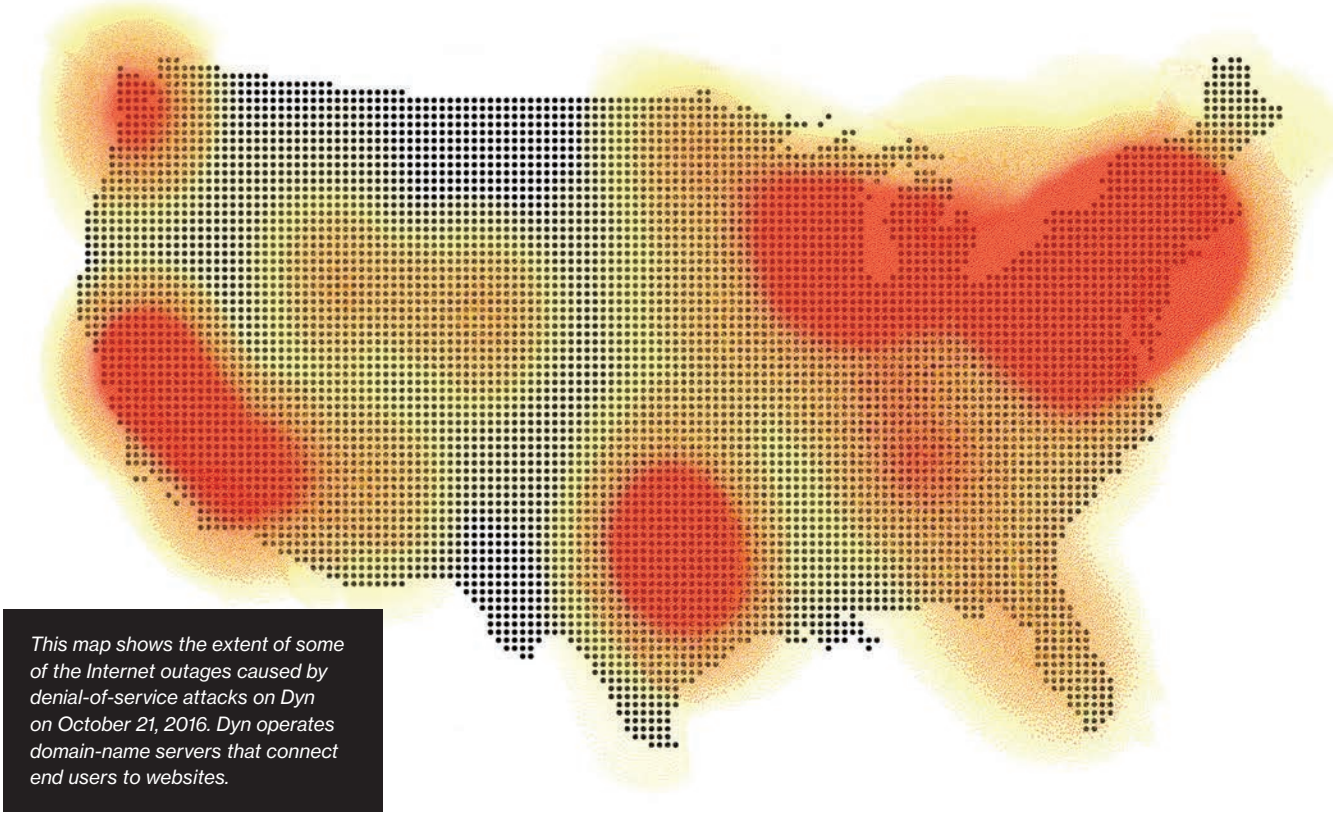
But now the problem is getting worse, thanks to a flood of cheap webcams, digital video recorders, and other gadgets in the "Internet of things." Because these devices typically have little or no security, hackers can take them over with little effort. And that makes it easier than ever to build huge botnets that take down much more than one site at a time.

In October, a botnet made up of 100,000 compromised gadgets knocked an Internet infrastructure provider partially offline. Taking down that provider, Dyn, resulted in a cascade of effects that ultimately caused a long list of high-profile websites, including Twitter and Netflix, to temporarily disappear from the Internet. More attacks are sure to follow: the botnet that attacked Dyn was created with publicly available malware called Mirai that largely automates the process of coöpting computers.

The best defense would be for everything online to run only secure software, so botnets couldn't be created in the first place. This isn't going to happen anytime soon. Internet of things devices are not designed with security in mind and often have no way of being patched. The things that have become part of Mirai botnets, for example, will be vulnerable until their owners throw them away. Botnets will get larger and more powerful simply because the number of vulnerable devices will go up by orders of magnitude over the next few years.

What do hackers do with them? Many things.

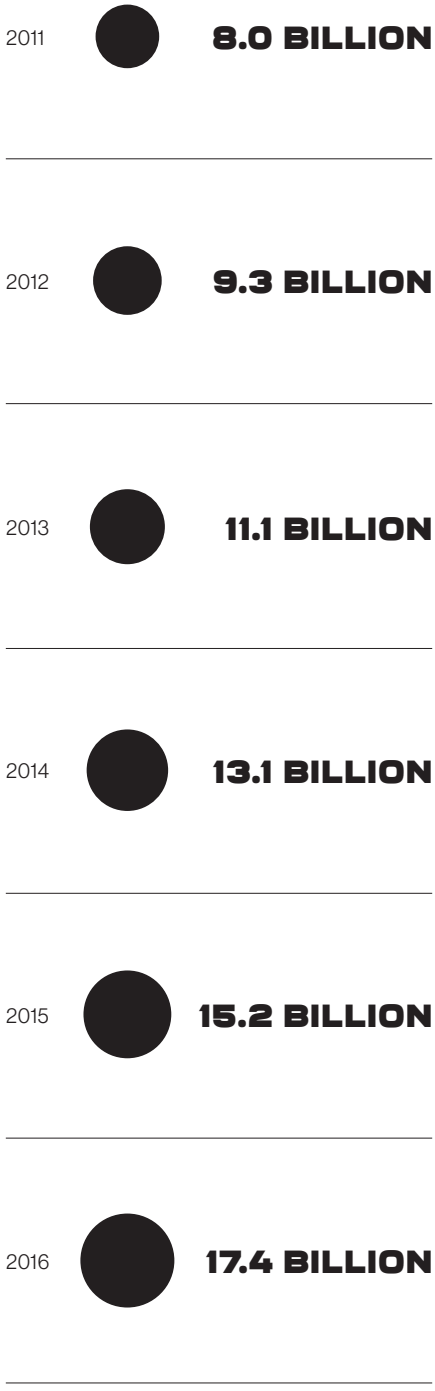
Botnets are used to commit click fraud. Click fraud is a scheme to fool advertisers into thinking that people are clicking on, or viewing, their ads. There are lots of ways to commit click fraud, but the easiest is probably for the attacker to embed a Google ad in a Web page he owns. Google ads pay a site owner according to the number of people who click on them. The attacker instructs all the computers on his botnet to repeatedly visit the Web page and click on the ad. Dot, dot, dot, PROFIT! If the botnet makers figure out more effective ways to siphon revenue from big companies online, we could see the whole advertising model of the Internet crumble.



This map shows the extent of some of the Internet outages caused by denial-of-service attacks on Dyn on October 21, 2016. Dyn operates domain-name servers that connect end users to websites.

OUTAGE DATA FROM DOWNDETECTOR

Worldwide number of "Internet-connectable" devices



DATA FROM IHS MARKIT

Botnets will get larger and more powerful simply because the number of vulnerable devices will go UP BY ORDERS OF MAGNITUDE OVER THE NEXT FEW YEARS.

Similarly, botnets can be used to evade spam filters, which work partly by knowing which computers are sending millions of e-mails. They can speed up password guessing to break into online accounts, mine bitcoins, and do anything else that requires a large network of computers. This is why botnets are big businesses. Criminal organizations rent time on them.

But the botnet activities that most often make headlines are denial-of-service attacks. Dyn seems to have been the victim of some angry hackers, but more financially motivated groups use these attacks as a form of extortion. Political groups use them to silence websites they don't like. Such attacks will certainly be a tactic in any future cyberwar.

Once you know a botnet exists, you can attack its command-and-control system. When botnets were rare, this tactic was effective. As they get more common, this piecemeal defense will become less so. You can also secure yourself against the effects of botnets. For example, several companies sell defenses against denial-of-service attacks. Their effectiveness varies, depending on the severity of the attack and the type of service.

But overall, the trends favor the attacker. Expect more attacks like the one against Dyn in the coming year.

Bruce Schneier, chief technology officer at IBM Resilient, is the author of 13 books on cryptography and data security.

Reviews

"The Relentless Pace of Automation"

Artificial intelligence could dramatically improve the economy and aspects of everyday life, but we need to invent ways to make sure everyone benefits.

By David Rotman

Last October, Uber had one of its self-driving trucks make a beer run, traveling 200 kilometers down the interstate to deliver a cargo of Budweiser from Fort Collins to Colorado Springs. A person rode in the truck but spent most of the trip in the sleeper berth, monitoring the automated system. (The test came just a few weeks after Uber had announced its driverless car service in Pittsburgh.) The self-driving truck developed by Uber's recently acquired Otto unit reflects remarkable technological achievements (see "10 Breakthrough Technologies: Self-Driving Trucks," page 62). It also provides yet another indicator of a looming shift in the economy that could have deep political consequences.

It is uncertain how long it will take for driverless trucks and cars to take over the roads. For now, any so-called autonomous vehicle will require a driver, albeit one who is often passive. But the potential loss of millions of jobs is Exhibit A in a report issued by the outgoing U.S. administration in late December. Written by President Obama's top economic and science advisors, "Artificial Intelligence, Automation, and the Economy" is a clear-eyed look at how fast-developing AI and automation technologies are affecting jobs, and it offers a litany of suggestions for how to deal with the upheaval.

"Artificial Intelligence, Automation, and the Economy"
Executive Office of the President
December 2016

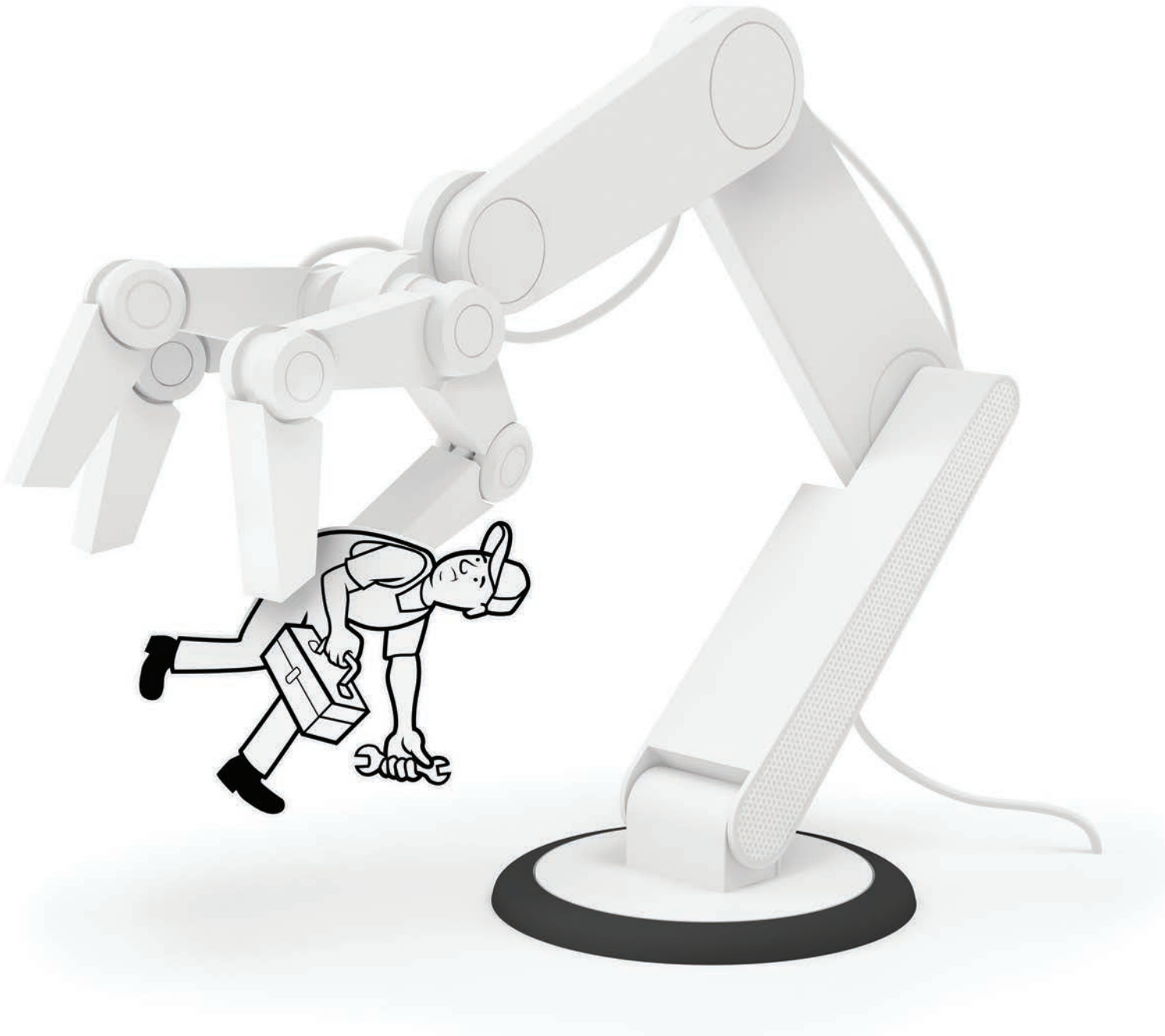
It estimates that automated vehicles could threaten or alter 2.2 million to 3.1 million existing U.S. jobs. That includes the 1.7 million jobs driving tractor-trailers, the heavy rigs that dominate the highways. Long-haul drivers, it says, "currently enjoy a wage premium over others in the labor market with the same level of educational attainment." In other words, if truck drivers lose their jobs, they'll be particularly screwed.

It is hard to read the White House report without thinking about the presidential election that happened six weeks before it was published. The election was decided by a few Midwest states in the heart of what has long been called the Rust Belt. And the key issue for many voters there was the economy—or, more precisely, the shortage of relatively well-paying jobs. In the rhetoric of the campaign, much of the blame for lost jobs went to globalization and the movement of manufacturing facilities overseas. "Make America great again" was, in some ways, a lament for the days when steel and other products were made domestically by a thriving middle class.

But many economists argue that automation bears much more blame than globalization for the decline of jobs in the region's manufacturing sector and the gutting of its middle class. Indeed, in his farewell speech to thousands in a packed convention hall in Chicago, President Obama warned: "The next wave of economic dislocations won't come from overseas. It will come from the relentless pace of automation that makes a lot of good middle-class jobs obsolete."

The White House report points in particular to the current wave of AI, which it describes as having begun around 2010. That's when advances in machine learning and the increasing availability of big data and enhanced computation power began providing computers with unprecedented capabilities such as the ability to accurately recognize images. The report says greater deployment of AI and automation could boost economic growth by creating new types of jobs and improving efficiency in many businesses. But it also points to the negative effects: job destruction and related increases in income inequality. For now at least, "less educated workers are more likely to be replaced by automation than highly educated ones." The report notes that so far automation has displaced few higher-skill workers, but it adds: "The skills in which humans have maintained a comparative advantage are likely to erode over time as AI and new technologies become more sophisticated."

Labor economists have been pointing out the employment consequences of new digital technologies for several years, and the White House report dutifully lays out many of those findings. As it notes, the imminent problem is not that robots will hasten the day when there is no need for human workers. That end-of-work scenario remains speculative, and the report pays it little heed. Instead, it is far more concerned with the transition in our economy that is already under way: the types of jobs available are rapidly changing. That's why the report is so timely. It is an attempt to elevate into



DELCAN & COMPANY

Washington political circles the discussion of how automation and, increasingly, AI are affecting employment, and why it's time to finally adopt educational and labor policies to address the plight of workers either displaced by technology or ill suited for the new opportunities.

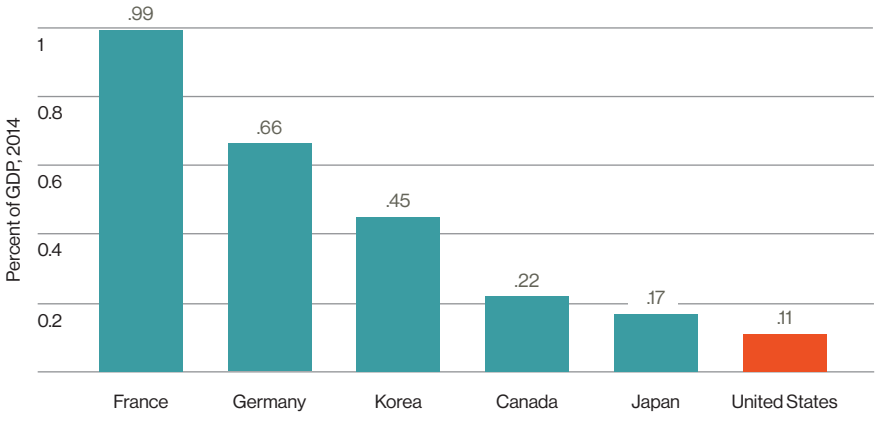
It is "glaringly obvious," says Daron Acemoglu, an economist at MIT, that political leaders are "totally unprepared" to deal with how automation is changing employment. Automation has been displacing workers from a variety of occupations, including ones in manufacturing. And now, he says, AI and the quickening deployment of robots in various industries, including auto manufacturing, metal products, pharmaceuticals, food service, and warehouses, could exacerbate the effects. "We haven't even begun the debate," he warns. "We've just been papering over the issues."

Left out

It is often argued that technological progress always leads to massive shifts in employment but that at the end of the day the economy grows as new jobs are created. However, that's a far too facile way of looking at the impact of AI and automation on jobs today. Joel Mokyr, a leading economic historian at Northwestern University, has spent his career studying how people and societies have experienced the

On Your Own

The U.S. government lags in spending on programs to help workers with economic transitions.



radical transitions spurred by advances in technology, such as the Industrial Revolution that began in the late 18th century. The current disruptions are faster and "more intensive," Mokyr says. "It is nothing like what we have seen in the past, and the issue is whether the system can adapt as it did in the past."

Mokyr describes himself as "less pessimistic" than others about whether AI will create plenty of jobs and opportunities to make up for the ones that are lost. And even if it does not, the alternative—technological stagnation—is far worse. But that still leaves a troubling quandary: how to help the workers left behind. "There is no question that in the modern capitalist system your occupation is your identity," he says. And the pain and humiliation felt by those whose jobs have been replaced by automation is "clearly a major issue," he adds. "I don't see an easy way of solving it. It's an inevitable consequence of technological progress."

The problem is that the United States has been particularly bad over the last few decades at helping people who've lost out during periods of technological change. Their social, educational, and financial problems have been largely ignored, at least by the federal government. According to the White House report, the U.S. spends around 0.1 percent of its GDP on programs designed to help people deal with changes in the workplace—far less than other developed economies. And this funding has declined over the last 30 years.

The picture is actually even worse than those numbers alone suggest, says Mark Muro, a senior fellow at the Brookings Institution. Existing federal "readjustment programs," he says, include a collection of small initiatives—some dating back to the 1960s—addressing everything from military-base closings to the needs of Appalachian coal-mining communities. But none are specifically designed to help people whose jobs have disappeared because of automation. Not only is the overall funding limited, he says, but the help is too piecemeal to take on a broad labor-force disruption like automation.

Some observers, spearheaded by a clique of Silicon Valley insiders, have begun arguing for a universal basic income as a way to help those unable to find work. Wisely, the White House report rejects such a solution as "giving up on the possibility of workers' remaining employed." As an alternative, Muro proposes what he calls a "universal basic adjustment benefit." Unlike the universal basic income, it would consist of targeted benefits for those seeking new job opportunities. It would provide such support as wage insurance, job counseling, relocation subsidies, and other financial and career help.

Such generous benefits are unlikely to be offered anytime soon, acknowledges Muro, who has worked with manufacturing communities in the Midwest (see "It's the Jobs, Stupid," January/February 2017). However, the presidential election, he suggests, was a wake-up call for many people. In some ways the result was "secretly about automation," he says. "There is a great sense of anxiety and frustration out there."

The question, then, is whether the looming onslaught of AI will make existing tensions even worse.

Cloudy days

No one actually knows how AI and advanced automation will affect future job opportunities. Predictions about what types of jobs will be replaced and how fast vary widely. One commonly cited study from 2013 estimated that roughly 47 percent of U.S. jobs could be lost over the next decade or two because they involve work that is easily automated. Other reports—noting that jobs often involve multiple tasks, some of which might be easily automated while others are not—have come up with a smaller percentage of occupations that machines could make obsolete. A recent study by the Organization for Economic Cooperation and Development estimates that around 9 percent of U.S. jobs are at high risk. But the other part of the employment equation—how many jobs will be created—is essentially unknowable. In 1980, who could have predicted this decade's market for app developers?

SOURCES: BROOKINGS INSTITUTION, OECD 2016

In the past, new technologies have greatly expanded overall employment opportunities. But no particular economic rule dictates that this will always be true. And some economists warn that we must not be overly sanguine about the consequences of automation and AI.

"AI is very much in its infancy," says MIT's Acemoglu. "We don't really know what it can do. It's too soon to know its impact on jobs." A key part of the answer, he says, will be to what extent the technologies are used to replace humans or, alternatively, to help them carry out their jobs and expand their capabilities. Personal computers, the Internet, and other technologies of the last several decades did replace some bank tellers, cashiers, and others whose jobs involved routine tasks. But mainly these technologies complemented people's abilities and let them do more at work, says Acemoglu. Will that pattern continue? "With robots, and down the line with artificial intelligence, the replacement part might be far stronger," he cautions.

Not only might automation and AI prove particularly prone to replacing human workers, but the effects might not be offset by the government policies that have softened the blow of such transitions in the past. Initiatives like improved retraining for workers who have lost their jobs to automation, and increased financial protections for those seeking new careers, are steps recommended by the White House report. But there appears to be no political appetite for such programs.

"I'm very worried that the next wave [of AI and automation] will hit and we won't have the supports in place," says Lawrence Katz, an economist at Harvard. Katz has published research showing that large investments in secondary education in the early 1900s helped the nation make the shift from an agriculture-based economy to a manufacturing one. And now, he says, we could use our education system much more effectively. For example, some areas of the United States have successfully connected training programs at community colleges to local companies and their needs, he says, but other regions have not, and the federal government has done little in this realm. As a result, he says, "large areas have been left behind."

One problem the growing adoption of AI could make much worse is income inequality (see "Technology and Inequality," November/December 2014) and the sharp divisions between the geographic areas that benefit and those that don't. We don't need the expert-written White House report to tell us that the impact of digital technologies and automation in large swaths of the Midwest is very different from the effects in Silicon Valley. A post-election analysis showed that one of the strongest predictors of voting behavior was not a county's unemployment rate or whether it was wealthy or poor but its share of jobs that are "routine"—economists' shorthand for ones that are easily automated. Areas with a high percentage of routine jobs overwhelmingly went for Donald Trump and his message of turning back the clock to "make American great again."

The economic anxiety over AI and automation is real and shouldn't be dismissed. But there is no reversing technological progress.

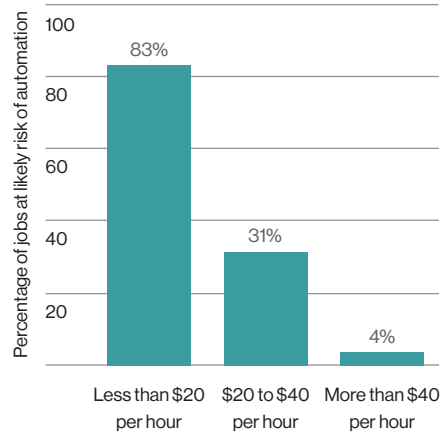
The economic anxiety over AI and automation is real and shouldn't be dismissed. But there is no reversing technological progress. We will need the economic boost from these technologies to improve the lackluster productivity growth that is threatening many people's financial prospects. Furthermore, the progress AI promises in medicine and other areas could greatly improve how we live. Yet if we fail to use the technology in a way that benefits as many people as possible (see "Who Will Own the Robots?" July/August 2015), we risk fueling public resentment of automation and its creators. The danger is not so much a direct political backlash—though the history of the Luddites suggests it could happen—but, rather, a failure to embrace and invest in the technology's abundant possibilities.

Despite the excitement around AI, it is still in its early days. Driverless vehicles are fine on sunny days but struggle in the fog or the snow, and they still can't be trusted in emergency situations. AI systems can spot complex patterns in massive data sets but still lack the common sense of a child or the innate language skills of a two-year-old. There are still very difficult technical challenges ahead. But if AI is going to achieve its full economic potential, we'll need to pay as much attention to the social and employment challenges as we do to the technical ones.

David Rotman is the editor of MIT Technology Review.

The Poor Get Poorer

Low-paying jobs are particularly vulnerable.



SOURCES: WHITE HOUSE AI REPORT, BASED ON BUREAU OF LABOR STATISTICS; FREY AND OSBORNE (2013); COUNCIL OF ECONOMIC ADVISERS

Virtually There

Traditional movies were the popular art form of the 20th century. Is virtual reality what comes next?

By Ty Burr

Would you watch a virtual-reality *Casablanca*?

The question is ridiculous, but usefully so. VR will never be like the movies, culturally or aesthetically, and the best way to understand why may be to imagine you're experiencing the 1942 Warner Brothers classic not as a linear story viewed from a theater seat, but as an immersive world accessed by a digital headset.

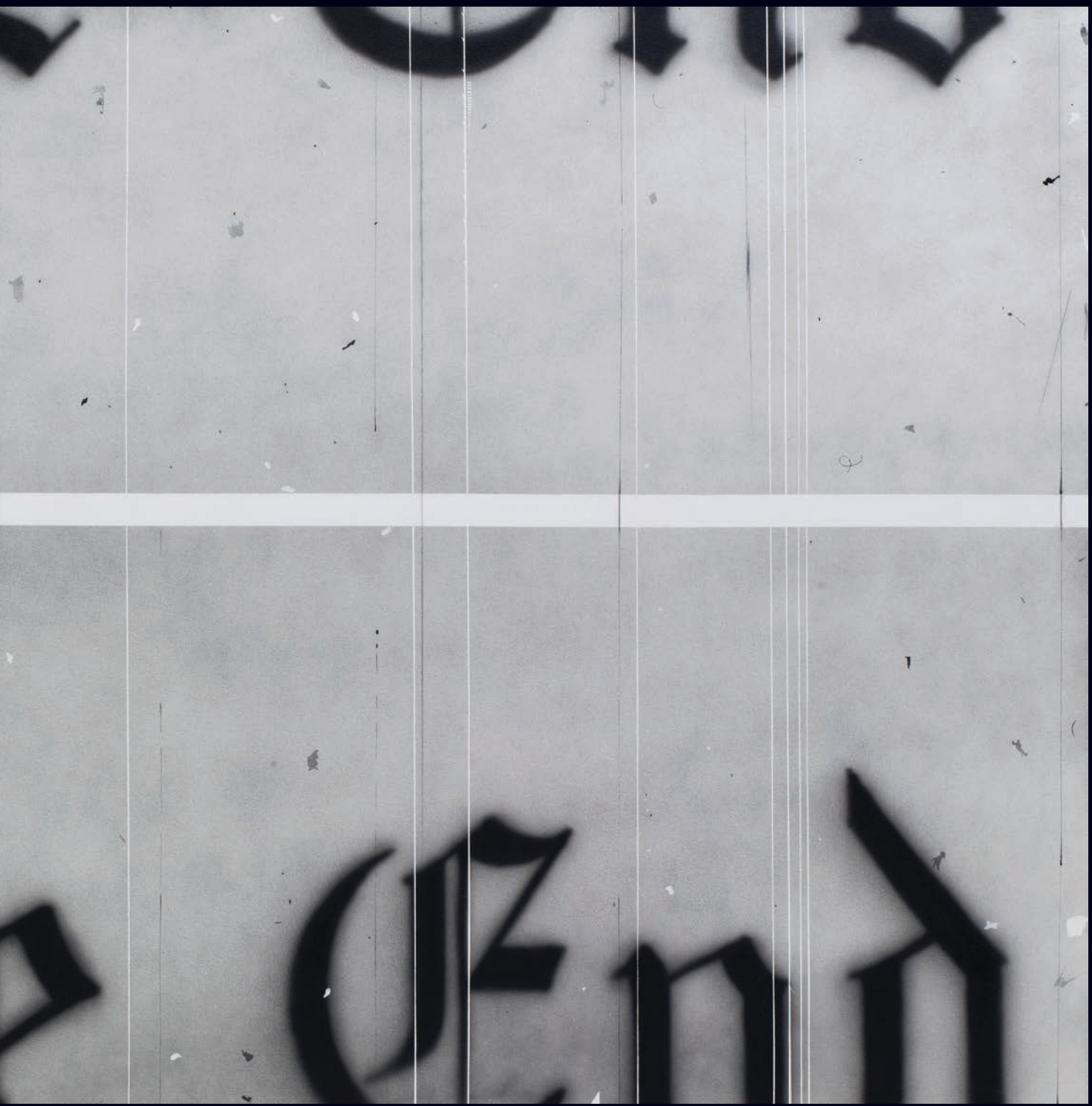
Most of us would never leave Rick's Café Américain. We'd go behind the bar with Sascha, hover by Emil the croupier at the roulette table, hang out with Sam as he played "As Time Goes By" again. Me, I'd be following Peter Lorre's sniveling Ugarte. But the central drama of Rick's rekindled love and sacrifice for Ilsa Lund? We'd probably never get that far. Director Michael Curtiz and the Warner Brothers elves did such a brilliant job imagining the world of *Casablanca* that we'd be content to explore it until we bumped up against the walls, like Jim Carrey in *The Truman Show*.

Similarly, a virtual-reality *Citizen Kane* might be a survey of the title character's infinite basement, each talisman sparking its own flashback in no particular order. *The Godfather VR Edition* might allow us to prowl the haunted house of Don Corleone's extended family, with the drama of Michael's slow rise and rot only one small thread amid the warp and weft.

VR will never become the new cinema. Instead, it will be a different thing. But what *is* that thing? And will audiences trained in passive linear narrative—where scene follows scene like beads on a string, and the string always pulls us forward—appreciate what the thing might be? Or will we only recognize it when the new medium has reached a certain maturity, the way audiences in 1903 sat up at *The Great Train Robbery* and recognized that, finally, here was a *movie*?

As a movie critic and a writer who has been covering film over 35 years, I recognize that I'm part of a vast viewership beholden to a media format that has passed its apogee: the roughly two-hour visual experience, usually narrative, pro-

Ed Ruscha
The End, 1991
Synthetic polymer paint and graphite on canvas
70 x 112 inches



jected on a screen for multiple viewers. We live in a time of cultural and technological upheaval, and traditional cinema was the art form of the 20th century. Distribution points are multiplying (TV, computer, phone) while viewing lengths run from binge-watched multi-hour TV episodes to 10-second Snapchats.

Once a technological Holy Grail or the province of science fiction films like *Brainstorm* (1983), *The Lawnmower Man* (1992), *The Matrix* (1999), and *Avatar* (2009), virtual-reality technology was for years bedeviled by image-rendering glitches and the vertigo that can afflict users trying to navigate a poorly created virtual space. It's hard to enjoy a fantasy world when you feel you're about to throw up. But now the future may finally be here. Consumer-ready VR helmets like the Oculus Rift, the Samsung Gear V12, Sony PlayStation VR, and the HTC Vive plunge viewers into immersive 3-D environments where they can move within a storyline or game space without feeling sick. They're the newest iterations of headsets that have been around for decades (I tested the CyberMaxx helmet for *Entertainment Weekly* way back in 1994), and they all descend from the first head-mounted display unit developed by computer scientist Ivan Sutherland in 1968, a behemoth so heavy that it was bolted to the ceiling and nicknamed the "Sword of Damocles."

Meanwhile, content creators—visual artists and game developers, filmmakers and other storytellers—are trying to figure out how it might work. (See an interview with Google's principal filmmaker for VR, Jessica Brillhart, on page 28.) Gaming software and networks represent the most fertile and obvious center of development, since exploring and interacting with a fictional reality *is* the plot of most video games. Other, more narrative virtual-reality experiences, available for purchase or free in the online VR stores that serve as visual entry points once you put on the Rift, the Gear, or the Vive, feel remarkably fresh. They point the way forward toward … *something*.

Sometimes that something can be startlingly beautiful. The 20-minute *Notes on Blindness: Into the Darkness* was much praised at the now-annual virtual-reality sidebar at the Sundance Film Festival last year, and it went on to win festival prizes throughout 2016. Based on the diaries of the late John Hull, a British writer and editor who lost his sight at age 45, *Notes* uses Hull's recorded voice as guide to an otherworld: a 360° panoramic London park, ink-black except for silhouetted outlines, that is illuminated by each sound we hear. A passing jogger's feet seem to bioluminesce with every clip-clop; the wind through the trees brings imagined color to branches and leaves. An entire landscape of synesthesia comes into being before our eyes and ears. Yes, it would and does work on a rectangular film or TV screen, but not nearly as convincingly as this immersive inner-yet-outer experience.

Notes on Blindness
free for Samsung Gear or Google Cardboard

Dear Angelica
free for Oculus

Invisible
free for most head-mounted displays on the Jaunt channel

Remembering Pearl Harbor
free for the Vive

Paul McCartney: Early Days
free on the Jaunt channel

The Rose and I
free for most head-mounted displays from Penrose Studios

Allumette
free from Penrose Studios

Even more striking is *Dear Angelica*, a highlight of this January's Sundance VR showcase. Directed by Saschka Unseld and developed in the skunk works of Oculus Story Studio, it's a memory play told from the point of view of a young woman, voiced by Mae Whitman, as she reminisces about her late mother, a larger-than-life film actress, voiced by Geena Davis. As with *Notes on Blindness*, there's no attempt to capture a photographic reality; rather, the artist Wesley Allsbrook has used the Quill VR illustration software, developed at Story Studio, to create a vivid impressionistic flow of color that evolves around, behind, and even beneath a viewer. *Dear Angelica* does move forward in linear fashion, but it doesn't tell a story so much as unfold like a poignant train of thought, and you can sense the filmmakers taking baby steps toward a new visual and psychological grammar.

These are beguiling visions, evidence of new ways of expressing human experiences, owing little to other media. Yet there are still stumbling blocks. For one thing, VR hardware is still very clumsy. You have to put on the headset, set up the movement tracking devices, log on to the computer, and avoid tripping over all those cords as you grope blindly about the rec room. It is as if Thomas Edison had told everyone that they needed to rewire their homes and assemble the projectors themselves if they ever wanted to watch a motion picture—and that they then had to put the projector on over their heads.

Most virtual-reality experiences that attempt to combine the narrative forward momentum of film with the immersive exploration of VR end up highlighting the worst of both mediums. Compared with the promise of *Notes on Blindness* and *Dear Angelica*, these "entertainments" represent the current reality of virtual reality, and it's worth talking about what they are and how you experience them.

The experiences are different on different headsets. Google Cardboard, an appealingly low-entry headset, lets you play VR content on an iPhone or Android phone slotted into a cardboard box; it's the VR equivalent of a Victorian stereoscope or a later generation's GAF View-Master, and while it's funky and the visuals can get mighty pixelated, it works. The Oculus Rift, available at electronics outlets for about $600 (hand controls are an additional $200), offers vastly improved visual resolution but requires a PC system with state-of-the-art graphic capability (at least $880) and a decent amount of technical

SARAH SHATZ/USA NETWORK

savvy to use. The more recently arrived HTC Vive has all that plus a pair of laser sensors that have to be precisely positioned on your walls so that the user's movements can be accurately tracked. (The Rift has a similar sensor that stands on a tabletop and looks like a microphone but isn't.) I didn't test-drive the Samsung Gear or other headsets for this article.

What are we able to dream while wearing these brave new goggles? In the virtual stores encountered once you put on the headsets—visual malls that seem to hover in space—you can pay for, collect, and access games, apps, social-media platforms, and a lot of what could be termed short VR programming, little of which is terribly interesting. You can watch brief comic skits—YouTube product busted out into 3-D—and travelogues that reinforce the View-Master comparison.

Doug Liman, the director of such Hollywood hits as *Swingers* (1996) and *The Bourne Identity* (2002), has produced and co-directed a VR series called *Invisible* for Jaunt, a VR production company and online store. In five episodes of about six minutes each, a clunky thriller storyline about invisible cousins comes to grief on soap-opera-level acting, dreadful writing, and an aesthetic that still owes much to traditional film. Each time the image cuts to a new angle, viewers have to joltingly reorient themselves in space. Still, a chase scene in Episode 5 shows some initiative in visualizing a 360° dramatic landscape.

Similarly, a short clip, *Mr. Robot VR,* available on a number of headsets, does little other than put the characters on a Coney Island Ferris wheel and allow the show's creator, Sam Esmail, to mess around with the new technology. Liman's *Swingers* star Jon Favreau—now a major Hollywood director himself (*Elf*, *The Jungle Book*)—has a more promising interactive project called *Gnomes & Goblins* in the works; a preview is currently available exclusively on the Vive.

Remembering Pearl Harbor, produced by Time Life and available on the Vive, lets you access archival historical recordings and material by wandering around and picking things up; it's well done, but it plays like a CD-ROM the company never got around to releasing in the 1990s. Jaunt also has some sort of deal with Paul McCartney that has resulted in VR concert documentaries (good) and *Paul McCartney: Early Days*, which simply puts Macca in a room and projects slide photos over his face while he talks about the young Beatles (not so good).

Some VR content houses have thought harder about the medium's possibilities. Penrose Studios has created two animated shorts for most VR platforms: *The Rose and I* and the excellent *Allumette* combine crude stop-motion-style graphics with engaging stories and a genuinely novel vantage point in which the viewer seems to hover in space; the Vive's motion tracking especially allows you to lean in, peer around, and get up close to the characters.

These are beguiling visions, evidence of new ways of expressing human experiences, owing little to other media.

For the more adventurous, there's a wealth of what might be called cottage-industry VR on the Internet, made by unaffiliated creators curious to push the boundaries of a new medium. Most of it involves 360° filmmaking, but only some of it is in 3-D, and very little involves motion tracking.

The high point of cottage-industry VR so far may be last year's *Career Opportunities in Organized Crime*, which billed itself as the first 360° feature-length VR movie. Directed by virtual-reality enthusiast (and radiologist) Alex Oshmyansky, *Career Opportunities* is about as crude as they come—it looks like something made in borrowed offices and someone's garage, and in fact it was. But there's a story of sorts there, about a Russian mobster with a human resources department and a slacker kid who locates his inner badass. Unfortunately, that's where the innovation stops. Almost all the dialogue-heavy scenes play out within a typical film screen, with little exploration of the medium's panoramic possibilities. One appeal of VR drama is its potential for surprise—for things to happen where you least expect them to.

Oshmyansky's film demonstrates a few things: first, that VR narrative entertainment may live closer to the aesthetics of theater than film (reverse theater-in-the-round, to be exact, with the viewer standing at the center of a 360° radius of action); and second, that a workable language of shots or other means of conveying information and directing audience attention has yet to be discovered. For now, what's still being sold in most cases is novelty—the fact that you're watching something supposedly more realistic than anything before—and not the experience itself. But realism shouldn't be the goal; a compelling immersive environment, whether it's reality- or fantasy-based, should be.

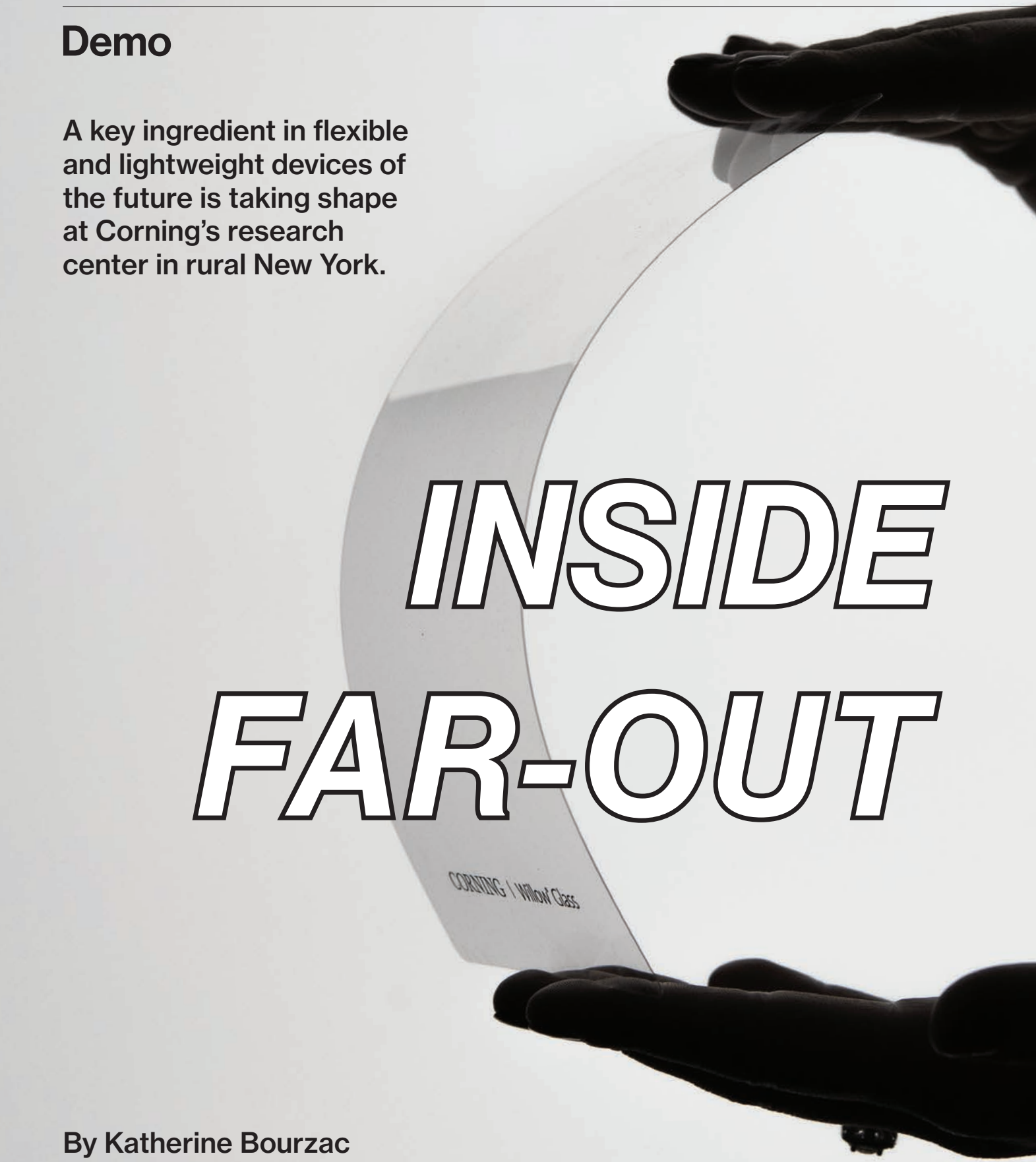
What's clear is that we're just at the beginning of VR's long gestational period, but the medium is established. The financial backing is there, as is the creative and technological drive to improve the experience. Eventually there will be a project (or two, or three) that will transform virtual reality from a curiosity to a genuine mass-appeal canvas for expression and entertainment. Works like *Allumette, Notes on Blindness,* and especially *Dear Angelica* point the way toward what VR might yet become, but it's almost impossible to describe what that may be. A movie that we seem to live? An adventure that doubles as a world? An immersive head trip, a tour of this and other planets, just another way to numb ourselves with fantasy? We lack words to describe the future because we haven't invented it yet.

Ty Burr is a film critic for the Boston Globe.

Demo

A key ingredient in flexible and lightweight devices of the future is taking shape at Corning's research center in rural New York.

INSIDE FAR-OUT



By Katherine Bourzac

MIT TECHNOLOGY REVIEW
VOL. 120 | NO. 2

Photographs by
Rachel Jerome Ferraro

THE GLASS LAB

Furnace workers at Corning's research melters, working in teams, wear silvery "bunny suits" when opening a 1,600 °C oven where experimental glass is melted.

At Corning's headquarters in upstate New York, three people in bulky masks and silvery, spacesuit-like gear are working the research furnaces. They move gracefully and in harmony. They have to, to face a 1,600 °C furnace, grab an incandescent crucible of molten glass, pour out the material, and shape it before it hardens. One worker's glove begins to smoke; he seems to pay it no mind.

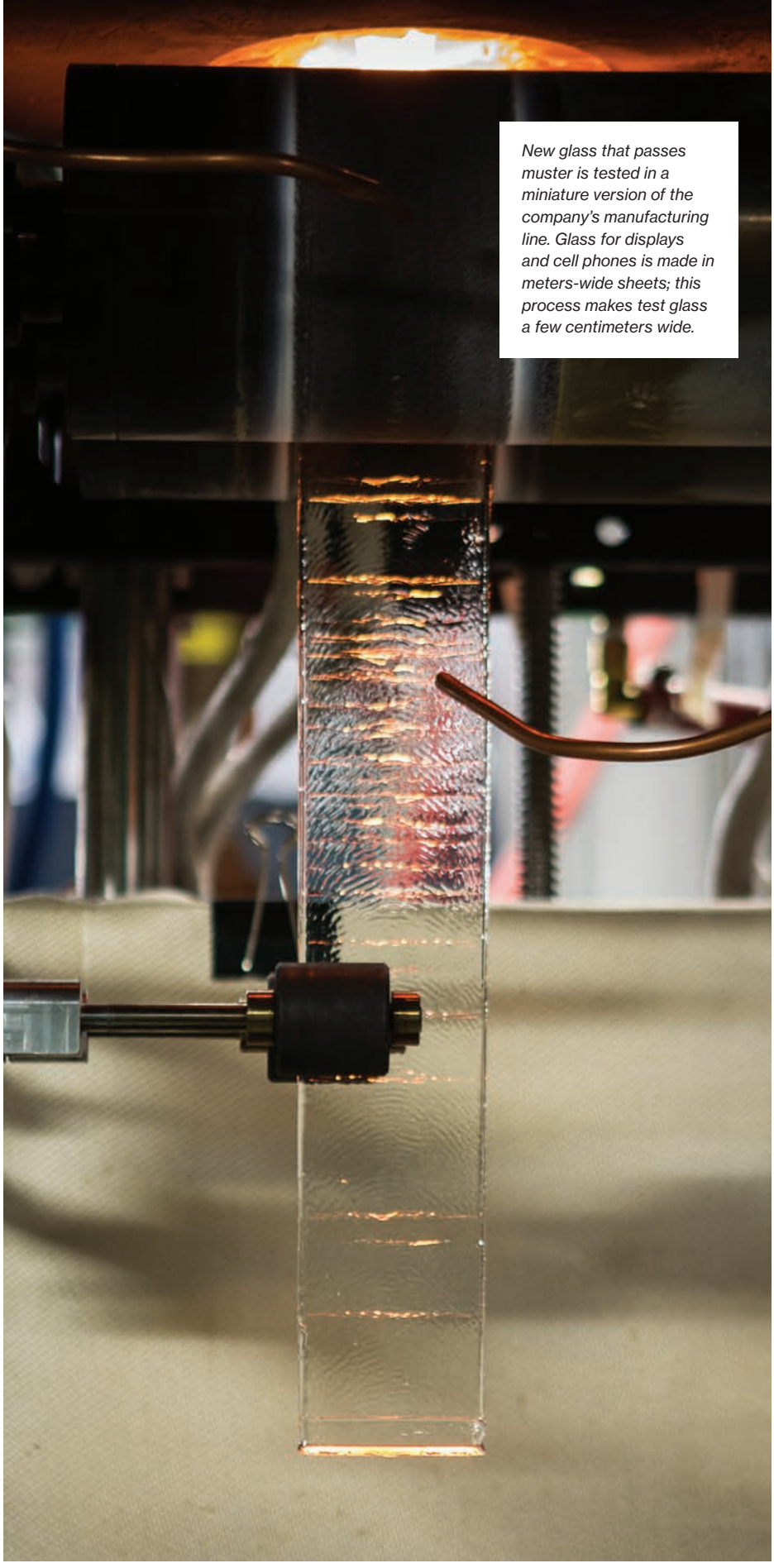
"They're doing a ballet," says Adam Ellison, a materials scientist at the company, watching the furnace workers as the glass dumps brimstone-like heat into the surrounding air. "It's hot as hell, the glass gets stiff very quickly, and you can only work with it for a few minutes," he says. Ellison would know—he helped develop the material they're pouring, which is branded Gorilla Glass and is found on many smartphones because it is tough, thin, and lightweight.

These researchers are helping Corning investigate just how much further it can push the properties of glass. If the company could make glass that is difficult to scratch and break but also bendy, it could

Potential products are subject to every kind of abuse engineers can think of and quantify.

Top: Workers pour the contents of a crucible of melted glass onto a metal table.

Bottom: A worker uses scissors to shape the glass into a puck for scientists to study. The glass quickly stiffens and begins to change color as it cools.

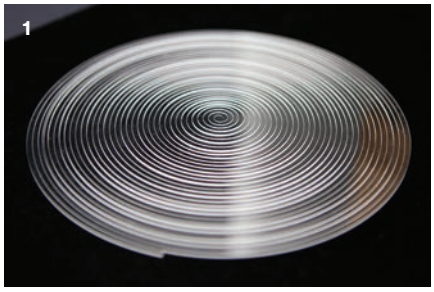


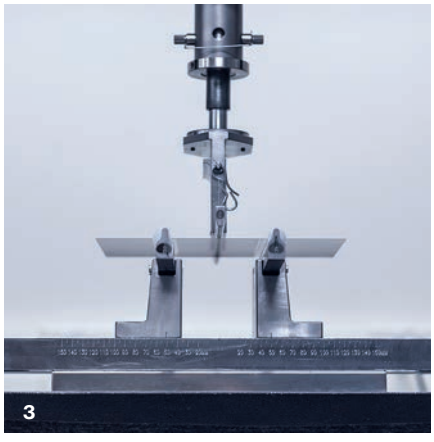
New glass that passes muster is tested in a miniature version of the company's manufacturing line. Glass for displays and cell phones is made in meters-wide sheets; this process makes test glass a few centimeters wide.

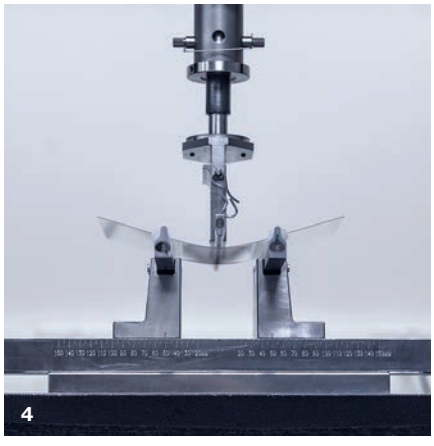
open up entirely new product categories: cell phones and tablets that fold or roll, for example. Thin, flexible glass might also turn curvy surfaces such as car interiors into touch-screen displays.

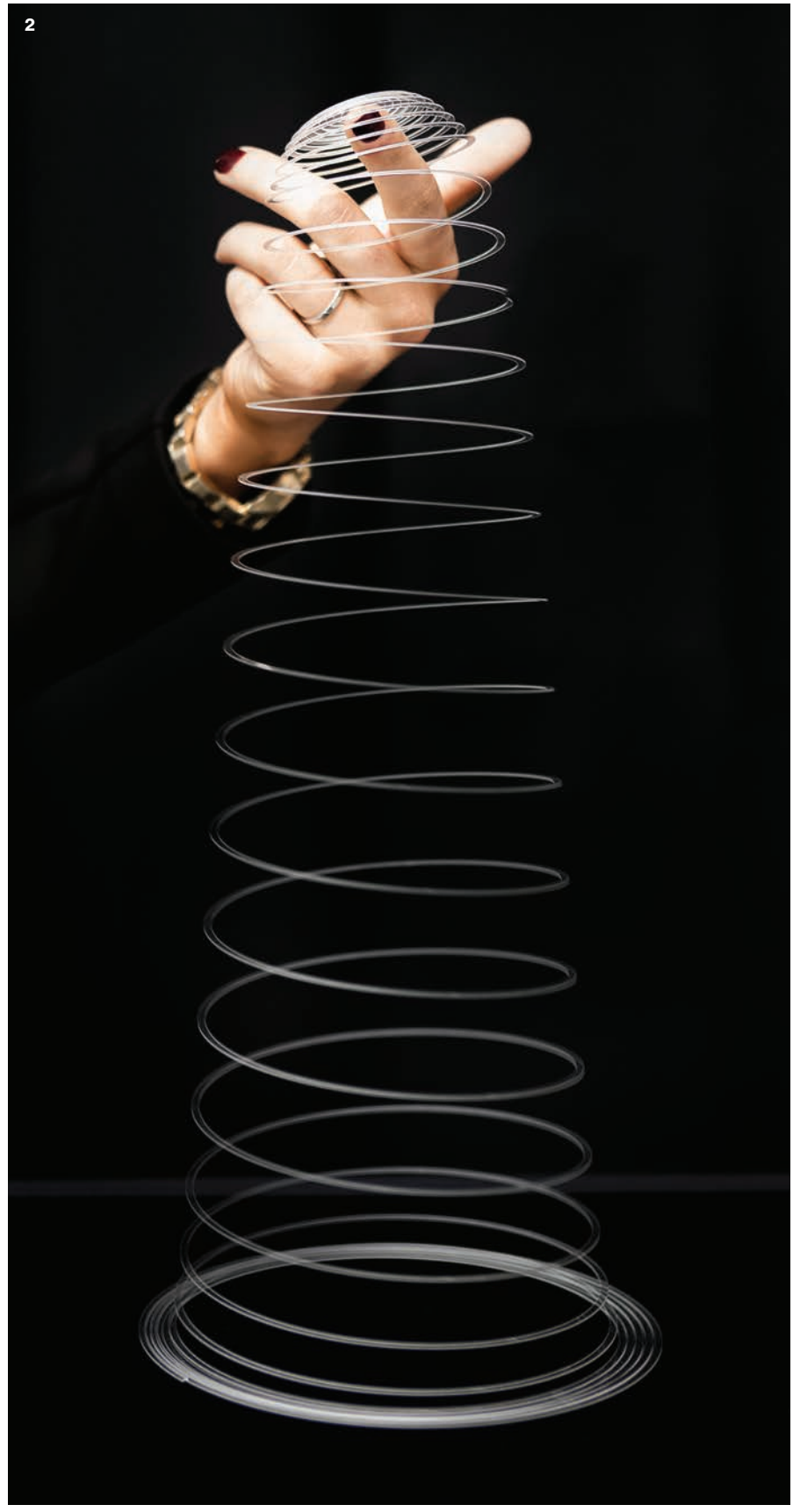
The research melter team prepares about eight to 12 experimental pours a day, providing samples for company scientists. The scientists want to know what will happen if they try something new, such as melting glass at a different temperature. The team also tests different manufacturing methods to see how they affect glass properties.

Potential new products are subject to every kind of abuse Corning engineers can think of and quantify. One machine repeatedly bends a thin piece of glass to see how long it will hold up; another machine bends glass in two until it shatters with an eardrum-shocking pop. Specialists in fractography—the science of how and why materials like glass fracture—use custom machines to measure the pressure required to fracture glass. With microscopes, researchers study the mechanical messages in the resulting crack pattern. Glass that's stronger will fracture with a large number of cracks; weaker glass cracks in only a few places. Materials that pass the test might next be made into cell-phone dummies and repeatedly dropped from waist height onto cement, gravel, and other surfaces.



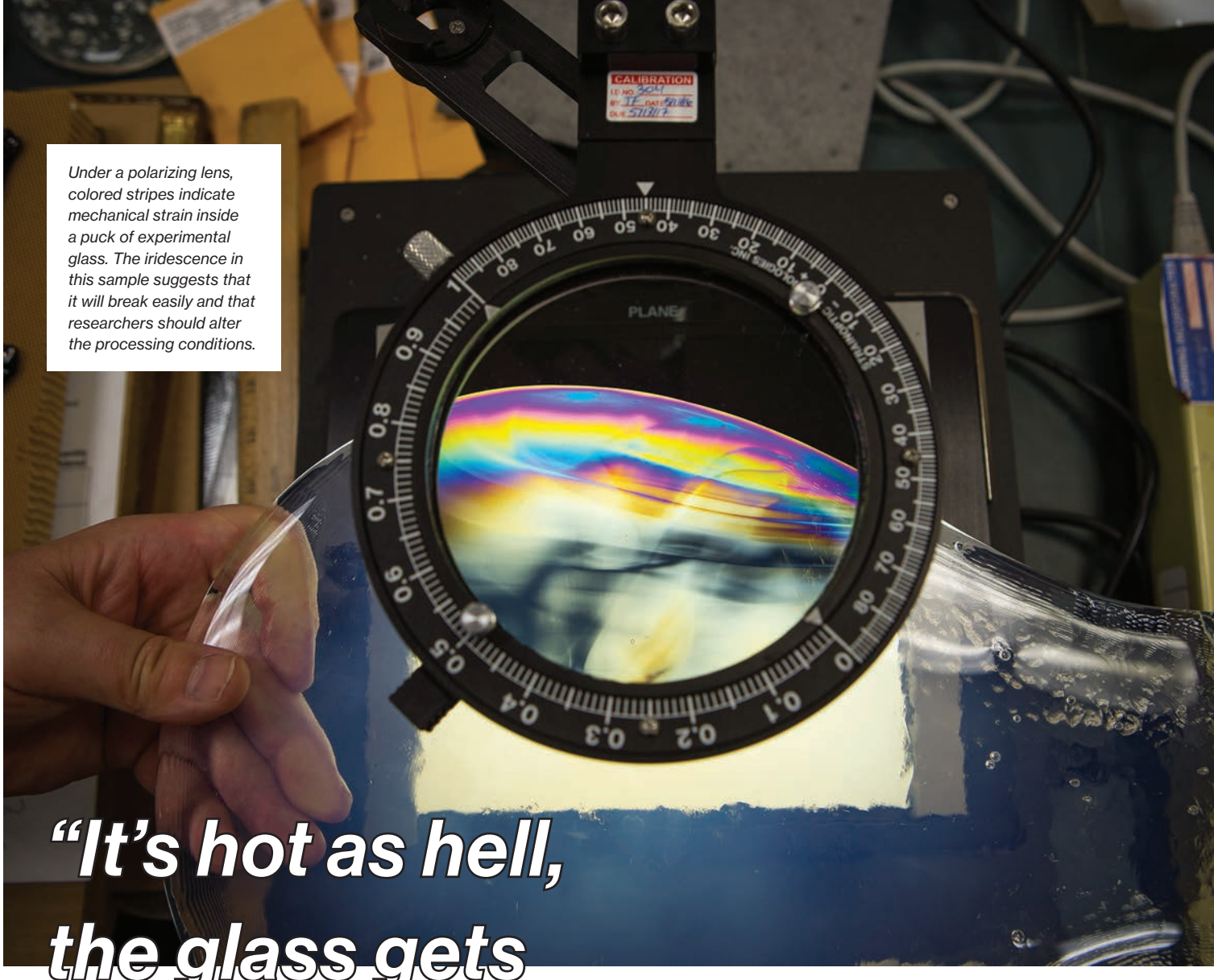






1-2 *Corning also develops new processes for handling glass, which can help device makers make custom pieces for new models of electronics. This ultrathin glass spiral was cut with a new laser machining process.*

3-4 *This machine bends a piece of flexible glass to determine how much stress it can take before it breaks. Researchers can then study the pattern of the fracture to learn how to make the glass more resilient.*



Under a polarizing lens, colored stripes indicate mechanical strain inside a puck of experimental glass. The iridescence in this sample suggests that it will break easily and that researchers should alter the processing conditions.

"It's hot as hell, the glass gets stiff very quickly, and you can only work with it for a few minutes."

Most of the company's research is on new manufacturing processes and gradual improvements of existing products like Gorilla Glass. But scientists also get to play around. One of Ellison's recent projects, for example, was to try to re-create the glass used to make the fourth-century Roman Lycurgus Cup. The goblet is cranberry red when lit from behind and jade green when lit from the front.

Ellison giddily shows off a sample of his Lycurgus-inspired glass, holding it up to a window to demonstrate the effect. "Now I know in detail why it does this," he says. Since he doesn't know what use such glass might have today or in the future, though, the recipe will go onto the shelf for a future employee to find.

40 Years Ago

Electronic Money Is Too Easy

In 1977, a writer worried that people might lose control if cash went away and transactions went digital.

"The era of Electronic Funds Transfer (EFT) is undoubtedly on its way. Auto-mated clearing houses have been set up to transfer payments from bank to bank via computer; pay-by-phone services are springing up; and electronic terminals are appearing in banks and stores to check credit and dispense cash.

The possibility that electronic cash might zip through the consumer's fingers faster than hard money worries Gordon B. Thompson of Bell Northern Research. Mr. Thompson wondered whether the combined impact of responsive cable TV and electronic money might tempt the shopper into impulsive video-shopping. 'The hard sell one sees on television could be directly coupled to a purchasing act,' said Mr. Thompson. 'By just inserting a credit card in the appropriate slot and pressing a button, the latest kitchen gizmo is on its way to the viewer's home, and his bank account will have been automatically adjusted.'

Electronic gambling could also be possible with the combined responsive cable TV/EFT systems, said Mr. Thompson. There could be ten-second lotteries, with painless payments made by simply slipping a credit card into the slot. [These systems could] bilk every compulsive gambler in the entire country.

EFT could make it possible to issue paychecks on a daily basis, and to pay bills on a daily basis ... It could be possible to control payments precisely for maximum benefits, for example, paying one's taxes precisely at 11:59 on April 15 of each year. Unfortunately, according to Robert H. Long and Wayne B. Lewin of the Bank Administration Institute, the government would probably already have gone to daily payment of taxes by then.

Other effects are not so obvious, said the two researchers. Because computers are more impersonal than human-centered systems, there might be an increase in 'beat the system' types of crimes. The challenge of the game of ripping off the computer may be just too much. 'The person who today tries to beat the house in Las Vegas ... might find the challenge of beating the electronic value transfer system too good to pass up. After all, who is hurt?' they asked.

Finally, and perhaps most ominously, the concentration of data in EFT systems will tempt greater government control of the economy, for huge amounts of economic data will be readily available, tempting policymakers to act upon it. And the power of EFT records may also tempt government to gather information on the habits and finances of the public, perhaps endangering privacy."

Excerpted from "Doubts About Electronic Money," from the February 1977 issue of Technology Review.

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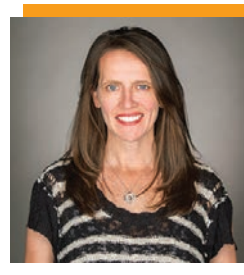

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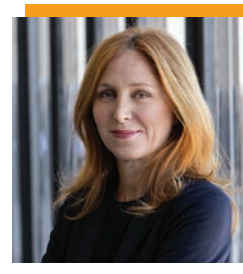
The Evolution of Alexa



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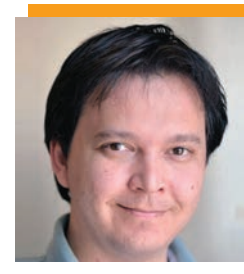

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