MIT Technology Review

VOL. 120 NO. 6 NOVEMBER/DECEMBER 2017
US $6.99/CAN $7.99

The Artificial Intelligence Issue

The End of the AI Boom?

The Billion-Dollar Quest to Have AI Keep You Healthy

What Everyone Gets Wrong When Making AI Predictions

Will Your Home Robot Have Feelings for You?

$6.99US $7.99CAN
DISPLAY UNTIL 01/02/2018

MIT Technology Review

EmTech DIGITAL

March 26-27, 2018

St. Regis Hotel

San Francisco, CA


Artificial intelligence is changing every business.
Don't be left behind.
Register Today:
technologyreview.com/aiexperience

The AI Issue

Brian Bergstein is **MIT Technology Review's** *editor at large.*

In his beautiful 2011 book *The Most Human Human: What Talking to Computers Teaches Us About What It Means to Be Alive*, Brian Christian shares his experience as a "human confederate" in a quirky contest known as the Loebner Prize. It's inspired by Alan Turing's proposal for how to gauge computer intelligence. In each round of the Loebner event, human judges sit at a computer and carry out text chats with two unseen interlocutors. One is a human and one is a software program—a chatbot. The judges must guess which is which, and the chatbot that most often gets mistaken for a human wins money for its programmer. As an aside, a second title is awarded as well, and that's the one that intrigued Christian. It goes to the person who was least likely to be mistaken for a computer: the most human human.

You can imagine the task facing a chatbot creator: combine language-processing code with rules of thumb about how one behaves in a conversation, and add just enough weirdness to keep the program from seeming robotic. But how should a human participant demonstrate the fact of being human through typed words alone? It's not obvious what aspects of your soul you ought to bare, what ineffable qualities you could signal that no machine could convincingly mimic.

The ideas Christian wrestled with—what cognition is, and what aspects of it are exclusively human—are ancient subjects in philosophy. But advances in artificial intelligence are about to force all of us to confront these questions in one way or another. What are the technological limits constraining how much of our economy and our daily lives might be automated? What's the best way to design computers so they augment human capabilities, making people and machines better together than either could be on their own?

That's the context for this special issue of *MIT Technology Review*.

AI is one of the most widely hyped technologies, but it's also easily misunderstood. To sort things out, we visit a pioneer of the much-heralded technique known as deep learning (see "Is AI Riding a One-Trick Pony?" on page 28). We explore the effects automation is having on labor ("India Warily Eyes AI," page 38). We introduce you to an entrepreneur who dreams of using AI to keep people healthy (page 46), and we explore how China's investments in the technology could alter the global economic order (page 66).

We offer no doomsday scenarios of out-of-control AI or extreme joblessness. Those outcomes seem unlikely for reasons Rodney Brooks describes on page 82. Besides, given the existential threats we actually face (environmental catastrophe, international conflict), it's unproductive to put AI on the list as another thing to fear. It's much more likely that people will use advanced computing to solve big problems, whether it's by finding medical cures, developing greener materials, or doing other things we can't yet envision.

However, if AI truly is to benefit all of humanity and not just exacerbate inequality, we need to be thoughtful about how it's built and who's building it, as Fei-Fei Li, Tabitha Goldstaub, and Cynthia Dwork discuss on pages 26, 45, and 53. And we ought to think carefully about how our new tools could change us, as Rana el Kaliouby (page 8) and Louisa Hall (page 74) explain. Imagination is required, because AI is still in its early days. Very human humans can still shape it.

ROXANA PERDUE


This is
a giant robot
monitored by
a flying robot.
GE's software and robotics innovations are helping new and existing energy sources run smarter and more efficiently. Join our drones for an exploration of the present and future of energy.
DRONEWEEK
Watch now on YouTube.com/GE

MIT TECHNOLOGY REVIEW
VOL. 120 | NO. 6
TECHNOLOGYREVIEW.COM

November/December 2017

The AI Issue

2 **From the Editor**

VIEWS

8 **Computers with Empathy**
Machines that detect feelings might boost our compassion.

UPFRONT

11 **Sickle-Cell Patients See Hope in CRISPR**
The disease is an early target for the gene-editing tool.

14 **Self-Driving Vehicles and the Angry-Trucker Problem**
Displaced workers could be eager hackers.

16 **The Cancer Vaccine That Too Many People Ignore**
Why isn't everyone getting the HPV vaccine?

And more.

Q&A

26 **Fei-Fei Li**
We need to emphasize the human side of technology.

REVIEWS

74 **On Robots with Feelings**
We're susceptible to thinking robots feel more than they do.

79 **The Seven Deadly Sins of AI Predictions**
Rodney Brooks says our view of the future is all wrong.

88 **Machine Hallucinations**

FEATURES

28 | **Is AI Riding a One-Trick Pony?**
The AI boom has been based on 30-year-old ideas. Without new ones, the revolution is over.
By James Somers

37 | **Fearsome Machines: A Prehistory**

38 | **India Warily Eyes AI**
Outsourcing, once a path to the middle class in India, is being wiped out by artificial intelligence.
By Samanth Subramanian

45 | **The Dangers of Tech-Bro AI**

46 | **Can AI Keep You Healthy?**
A Chinese entrepreneur wants to prevent disease by constantly testing your body for everything.
By David Ewing Duncan

53 | **How to Root Out Hidden Bias in AI**

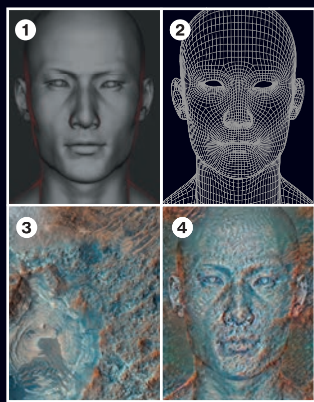
54 | **A Moonshot to Understand the Brain**
AI is loosely modeled on the brain, but until now we've barely understood how the brain works.
By M. Mitchell Waldrop

64 | **Fiction That Gets AI Right**

66 | **China's AI Awakening**
The West shouldn't fear China's AI revolution. It should copy it.
By Will Knight

73 | **Don't Let Regulators Ruin AI**

ON THE COVER



For our cover, artist Timothy Luke began by rendering an image of a stock model's face in Cinema 4D (image 1) and then output a low-poly wireframe of the same face (2). Using a tool from DeepArt.io, based on a convolutional neural network, he then ran the render against an image of the Mars surface obtained from HiRISE, a camera on board the Mars Reconnaissance Orbiter (3), creating the high-resolution output on the right (4). The final image was adjusted and converted for print (5), then combined into a tryptic with the original render image elements (6).

Illustration by Timothy Luke

COURTESY OF LICHTMAN LAB; CINEMA 4D; NASA/JPL/UNIVERSITY OF ARIZONA; DEEPART.IO

CUSTOMER SERVICE AND SUBSCRIPTION INQUIRIES

National
800-877-5230

International
903-636-1115

E-mail
customer_service@mittechnologyreview.info

Web
www.technologyreview.com/customerservice

MIT Records (alums only)
617-253-8270

Reprints
techreview@wrightsmedia.com
877-652-5295

Licensing and permissions
licensing@technologyreview.com

Technology Review
One Main Street, 13th Floor
Cambridge, MA 02142
Tel: 617-475-8000

The mission of *MIT Technology Review* is to equip its audiences with the intelligence to understand and contribute to a world shaped by technology.

Technology Review, Inc., is an independent nonprofit 501(c)(3) corporation wholly owned by MIT; the views expressed in our publications and at our events are not always shared by the Institute.

Views

COMPUTING

We Need Computers with Empathy

An emerging trend in artificial intelligence is to get computers to detect how we're feeling and respond accordingly. They might even help us develop more compassion for one another.

I was rehearsing a speech for an AI conference recently when I happened to mention Amazon Alexa. At which point Alexa woke up and announced: "Playing Selena Gomez." I had to yell "Alexa, stop!" a few times before she even heard me.

But Alexa was oblivious to my annoyance. Like the majority of virtual assistants and other technology out there, she's clueless about what we're feeling.

We're now surrounded by hyper-connected smart devices that are autonomous, conversational, and relational, but they're completely devoid of any ability to tell how annoyed or happy or depressed we are. And that's a problem.

What if, instead, these technologies—smart speakers, autonomous vehicles, television sets, connected refrigerators, mobile phones—were aware of your emotions? What if they sensed nonverbal behavior in real time? Your car might notice that you look tired and offer to take the wheel. Your fridge might work with you on a healthier diet. Your wearable fitness tracker and TV might team up to get you off the couch. Your bathroom mirror could sense that you're stressed and adjust the lighting while turning on the right mood-enhancing music. Mood-aware technologies would make personalized recommendations and encourage people to do things differently, better, or faster.

Today, an emerging category of AI—artificial emotional intelligence, or emotion AI—is focused on developing algorithms that can identify not only basic human emotions such as happiness, sadness, and anger but also more complex cognitive states such as fatigue, attention, interest, confusion, distraction, and more. (As for whether machines could not only detect emotions but also experience their own, see "How We Feel About Robots That Feel," page 74.)

My company, Affectiva, is among those working to build such systems. We've compiled a vast corpus of data consisting of six million face videos collected in 87 countries, allowing an AI engine to be tuned for real expressions of emotion in the wild and to account for cultural differences in emotional expression.

Using computer vision, speech analysis, and deep learning, we classify facial and vocal expressions of emotion. Quite a few open challenges remain—how do you train such multi-modal

Rana el Kaliouby

ANDY FRIEDMAN

systems? And how do you collect data for less frequent emotions, like pride or inspiration?

Nonetheless, the field is progressing so fast that I expect the technologies that surround us to become emotion-aware in the next five years. They will read and respond to human cognitive and emotional states, just the way humans do. Emotion AI will be ingrained in the technologies we use every day, running in the background, making our tech interactions more personalized, relevant, authentic, and interactive. It's hard to remember now what it was like before we had touch interfaces and speech recognition. Eventually we'll feel the same way about our emotion-aware devices.

I expect the technologies that surround us to become emotion-aware in the next five years.

Here are a few of the applications I'm most excited about.

Automotive: An occupant-aware vehicle could monitor the driver for fatigue, distraction, and frustration. Beyond safety, your car might personalize the in-cab experience, changing the music or ergonomic settings according to who's in the car.

Education: In online learning environments, it is often hard to tell whether a student is struggling. By the time test scores are lagging, it's often too late—the student has already quit. But what if intelligent learning systems could provide a personalized learning experience? These systems would offer a different explanation when the student is frustrated, slow down in times of confusion, or just tell a joke when it's time to have some fun.

Health care: Just as we can track our fitness and physical health, we could track our mental state, sending alerts to a doctor if we chose to share this data. Researchers are looking into emotion AI for the early diagnosis of disorders such as Parkinson's and coronary artery disease, as well as suicide prevention and autism support.

Communication: There's a lot of evidence that we already treat our devices, especially conversational interfaces, the way we treat each other. People name their social robots, they confide in Siri that they were physically abused, and they ask a chatbot for moral support as they head out for chemotherapy. And that's before we've even added empathy. On the other hand, we know that younger generations are losing some ability to empathize because they grow up with digital interfaces in which emotion, the main dimension of what makes us human, is missing. So emotion AI just might bring us closer together.

As with any novel technology, there is potential for both good and abuse. It's hard to get more personal than data about your emotions. People should have to opt in for any kind of data sharing, and they should know what the data is being used for. We'll also need to figure out if certain applications cross moral lines. We'll have to figure out the rules around privacy and ethics. We'll have to work to avoid building bias into these applications. But I'm a strong believer that the potential for good far outweighs the bad.

Rana el Kaliouby is the CEO and cofounder of Affectiva. In 2012 she was named one of MIT Technology Review*'s 35 Innovators Under 35.*

Upfront

DAVID BRANDON GEETING

Sickle-Cell Patients See Hope in CRISPR

The disease may be among the first to be treated with the novel gene-editing tool.

Hertz Nazaire is a soft-spoken artist who likes to paint in bright colors, with subjects like rainbow palm leaves and dancing women in twirling skirts. But one series of paintings he's created is darker. Here, deep-red discs contrast with misshapen, bluish-purple ones against a black background. One canvas shows a face drowning in the red and blue shapes,

Upfront

eyes streaming with tears, mouth agape in pain. The work reflects his lifelong struggle with sickle-cell disease.

Nazaire, a 43-year-old Haitian-American, figures he's been hospitalized more than 300 times since he was a child. He and other sickle-cell patients will tell you that the worst part of the disease is the debilitating pain. "It's a horrifying thing to have, because it's extremely painful. It's a major fight all the time," he says.

Roughly 100,000 people in the U.S. have sickle-cell disease, most of them African-Americans and Latinos but also people of Middle Eastern, Asian, Indian, and Mediterranean descent. Compared with the average American, they live much shorter lives—about 40 to 60 years.

The cause of sickle-cell has been known for a century, but the disease has long been underserved by the medical establishment and the pharmaceutical industry. That may be about to change. Its genetic origin—a single, well-studied mutation—makes it an attractive candidate for treatment with the gene-editing tool CRISPR.

The idea is that CRISPR could correct the genetic mutation responsible for sickle-cell so that patients' bodies could make normal red blood cells, alleviating the pain and other severe symptoms associated with the disease. Researchers have already tested the gene-editing tool on human sickle cells in the lab and are now working on getting the technique to clinical trials. Early results hint that sickle-cell could be among the first diseases that CRISPR essentially cures.

Despite the lingering safety concerns about using CRISPR in people, some sickle-cell patients and their doctors are already embracing it. "I would be one of the first people to volunteer and say, 'I want to take part in a study,'" Nazaire says. He first heard about CRISPR two years ago, when he came across a YouTube video featuring Jennifer Doudna and Emmanuelle Charpentier, two of the inventors of the technology. He's been enthusiastic about the idea of using CRISPR to treat sickle-cell ever since.

Sickle-cell disease is one of the most common genetic disorders, affecting millions of people around the world. It's caused by a mutation in a gene known as *HBB*, which makes hemoglobin, a protein that transports oxygen throughout the body. Blood cells with healthy hemoglobin are red and disc-shaped. Cells with abnormal hemoglobin are shaped like sickles used to cut wheat, the characteristic that gives the disease its name.

These misshapen cells are sticky and clump together. When too many of them build up, they create blockages in blood vessels and cut off oxygen to nearby parts of the body, causing severe episodes of pain. The disease can also cause frequent infections, eye problems, and organ damage.

"I would be one of the first people to volunteer and say, 'I want to take part in a study.'"

CRISPR Therapeutics is one of a handful of gene-editing startups pursuing new treatments for sickle-cell. The company's approach involves isolating stem cells from samples of patients' blood. Scientists would use CRISPR to activate a genetic switch that would raise the levels of a fetal form of hemoglobin in red blood cells, turning them healthy. This fetal hemoglobin effectively counteracts the effects of the sickle mutation. The modified cells would then be infused back into the patients.

Samarth Kulkarni, president of CRISPR Therapeutics, says this is safer than injecting the gene-editing mechanism directly into the patient. That's risky because CRISPR can cause unintentional or off-target edits, meaning it may cut DNA it isn't supposed to. Editing cells outside the body will allow scientists to make sure the technique works before reintroducing the cells, he says.

Testing the method in lab experiments using stem cells taken from sickle-cell patients, researchers at CRISPR Therapeutics found that 85 percent of the cells were successfully edited, which means they were able to make healthy red blood cells. Kulkarni says when the stem cells are reintroduced into the patient, they should be able to ameliorate all symptoms of sickle-cell. These stem cells are able to travel to the bone marrow, where they make more healthy blood cells for the rest of the body. The healthy cells will proliferate, and eventually, he says, they will outnumber the sickled ones. St. Jude Children's Research Hospital, Editas Medicine, and Intellia Therapeutics are working on similar approaches.

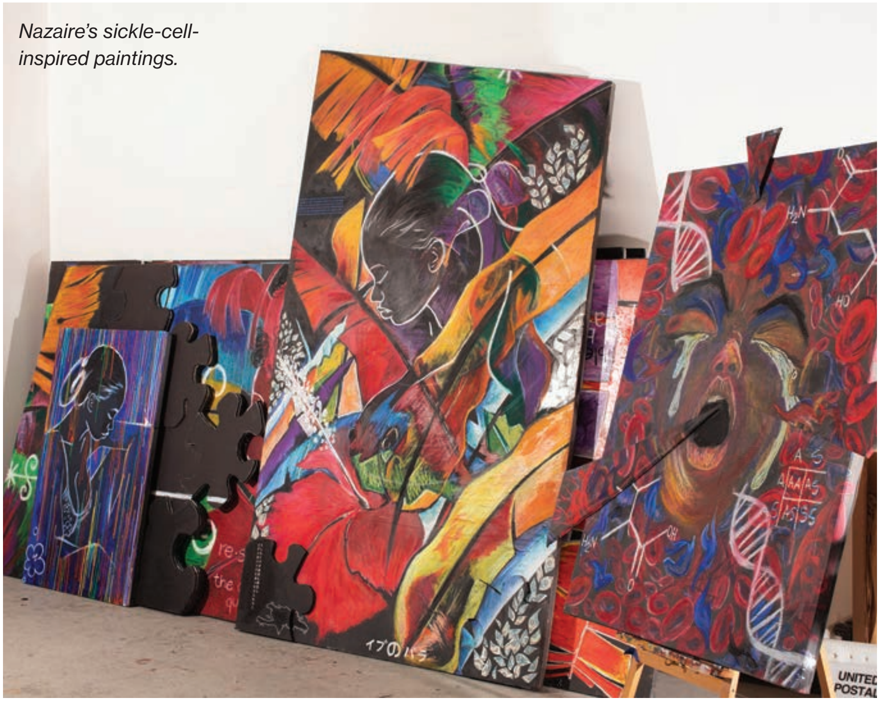
Meanwhile, researchers at Stanford University School of Medicine are working on a different method that aims to directly modify the mutated *HBB* gene itself using CRISPR. Researchers would do that outside the body as well. Matthew Porteus, an associate professor of pediatrics at Stanford, says his team is aiming to begin a clinical trial by early 2019.

Porteus says not all of a patient's original sickle cells need to be replaced with edited ones to effectively cure the disease. He says if the proportion of sickle cells is below 30 percent, patients don't have any symptoms. So far, his team has been able to achieve correction rates between 40 and 70 percent. He expects corrected blood cells to eventually surpass sickled ones in a patient's body. Sickle cells live only 10 to 20 days, but normal red blood cells last from 90 to 120 days.

The first clinical trials using CRISPR haven't started in the U.S. yet, but researchers are already taking steps to educate patients about the technology. The National Institutes of Health is launching a study this month to examine opinions on CRISPR among up to 150 sickle-cell patients, parents of patients, and health-care providers.

Vence Bonham, a researcher on genomics and health disparities at the National Human Genome Research Institute who is leading the study, says it's important that scientists designing clinical trials consider patients' beliefs and concerns. Gauging the views of people who are most likely to be affected by a new scientific advance seems like a no-brainer, but it's something that's rarely been done in medical research. "This technology has been moving very quickly, but the disease and advocacy communities have not really been part of the conversation," Bonham says.

Participants in the NIH study will first be asked about their knowledge of CRISPR. Then they'll watch an educational video about the technology and answer a second set of questions to see how the video may have influenced their knowledge or beliefs. After that, they'll participate in focus groups with other patients, parents of patients, or health-care providers to talk about using CRISPR for sickle-cell disease. Bonham hopes the study will "inform the development of clinical trials to make them more appropriate and respectful of the concerns of the community."



Nazaire's sickle-cell-inspired paintings.

DAVID BRANDON GEETING

Biree Andemariam, director of the New England Sickle Cell Institute at the University of Connecticut Health Center, has talked to her adult patients about CRISPR's potential for treating sickle-cell disease. "Patients are very intrigued by it. They think it sounds wonderful," she says.

But Andemariam says there can also be trust issues between sickle-cell patients and their health-care providers. Black patients may be suspicious of signing up for clinical trials, particularly given historical examples of medical experimentation on African-Americans without their consent. The infamous Tuskegee study, for example, left African-American men with syphilis deliberately untreated in an experiment that ran from 1932 to 1972.

"The Tuskegee experiment is fresh in a lot of people's minds even though that was decades ago," says Andemariam, who is also chief medical officer for the Sickle Cell Disease Association of America.

If a CRISPR cure for sickle-cell eventually reaches the market, one major question is who will have access to it. Isaac Odame, a Ghana-born physician at the Hospital for Sick Children in Toronto, says patients in Africa already have trouble paying for hydroxyurea, a common medication used to treat the disease. The drug costs one to two dollars per day, but even that is too expensive for many, he says. He worries the cost of CRISPR will put a cure out of reach for most of the world's patients.

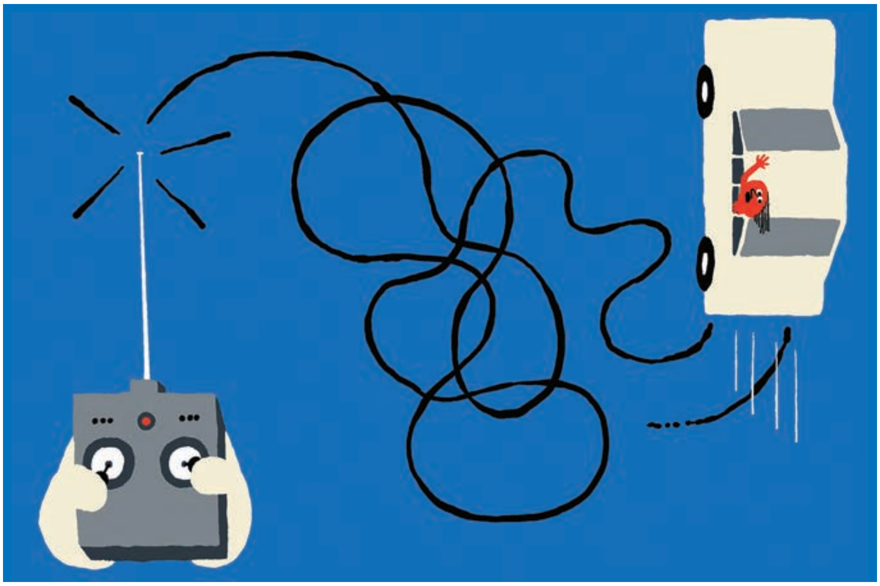
"For 90 percent of people with sickle-cell disease who live in this world, this will still be something far too expensive for them to have access to," he says.

Until CRISPR is available, sickle-cell patients will have to cope with other treatments. To manage his disease, Nazaire recently underwent apheresis, a transfusion procedure that removed and replaced some of his red blood cells in an attempt to decrease the proportion of sickled ones. He's in less pain than before, but the benefits could wear off over time.

To Nazaire and others, CRISPR represents the promise of a better, longer life. "When you're faced with something that's desperate and life-threatening, you want to see something done about it," he says. "I think this is something that needs to be used. It could be beneficial for the world."

—Emily Mullin

Upfront



How Angry Truckers Might Sabotage Self-Driving Cars

Displaced workers armed with "adversarial machine learning" could dazzle autonomous vehicles into crashing.

Before autonomous trucks and taxis hit the road, manufacturers will need to solve problems far more complex than collision avoidance and navigation. These vehicles will have to anticipate and defend against a full spectrum of malicious attackers wielding both traditional cyberattacks and a new generation of attacks based on so-called adversarial machine learning.

There have been no reports to date of hostile hackers targeting self-driving vehicles. But there were no malicious attackers when the dot-com startups in the 1990s developed the first e-commerce platforms, either. After the first big round of e-commerce hacks, Bill Gates wrote a memo to Microsoft demanding that the company take security seriously. The result: today Windows is one of the most secure operating systems, and Microsoft spends more than a billion dollars annually on cybersecurity. Yet hackers keep finding problems with Windows operating systems.

Car companies are likely to go through a similar progression. After being widely embarrassed by their failure to consider security at all, they now appear to be paying attention. When hackers demonstrated that vehicles were vulnerable to several specific security threats, automakers responded by recalling and upgrading the firmware of millions of cars. Last July, GM CEO Mary Barra said that protecting cars from a cybersecurity incident "is a matter of public safety."

But current efforts may be missing the next security trend. The computer vision and collision avoidance systems under development for autonomous vehicles rely on complex machine-learning algorithms that are not well understood, even by the companies that rely on them.

Last year researchers at Carnegie Mellon University demonstrated that state-of-the-art face recognition algorithms could be defeated by wearing a pair of clear glasses with a funky pattern printed on their frames. Something about the pattern tipped the algorithm in just the right way, and it thought it saw what wasn't there. Also last year, researchers at the University of South Carolina, China's Zhejiang University, and the Chinese security firm Qihoo 360 demonstrated that they could jam various sensors on a Tesla S, making objects invisible to its navigation system.

Why would anyone want to hack a self-driving car, knowing that it could cause death? One reason is that autonomous vehicles could leave a lot of people unemployed, and some of them are going to be angry.

In 2016, Ford CEO Mark Fields said that he planned to have fully autonomous vehicles operating as urban taxis by 2021. Google, Nissan, and others planned to have similar autonomous cars on the roads as soon as 2020. Those automated taxis or delivery vehicles could be vulnerable to being maliciously dazzled with a high-power laser pointer by an out-of-work Teamster, a former Uber driver, or just a pack of bored teenagers.

Asked about Uber's plans for addressing the threat of adversarial machine learning, Sarah Abboud, a spokesperson for the company, responded: "Our team of security experts are constantly exploring new defenses for the future of autonomous vehicles, including data integrity and abuse detection. However, as autonomous technology evolves, so does the threat model, which means some of today's security issues will likely differ from those addressed in a truly autonomous environment."

—Simson Garfinkel

ESPEN FRIBERG

Another Way AI Programs Can Discriminate Against You

Voice interfaces, chatbots, and other artificial-intelligence systems can be biased against certain minority dialects.

All too often people make snap judgments based on how you speak. Some AI systems are also learning to be prejudiced against certain dialects. And as language-based AI systems become ever more common, machines may automatically discriminate against minorities, warn researchers studying the issue.

Anyone with a strong or unusual accent may know what it's like to have trouble being understood by Siri or Alexa. This is because voice-recognition systems use natural-language technology to parse the contents of speech, and it often relies on algorithms that have been trained with example data. If there aren't enough examples of a particular accent or vernacular, then these systems may simply fail to understand you.

But the problem may be more widespread and pernicious than most people realize. Natural-language technology now powers interactions with customers, through automated phone systems or chatbots. It's used to mine public opinion on the Web and social networks, and to comb through written documents for useful information. This means that services and products built on top of language systems may already be unfairly discriminating against certain groups.

Brendan O'Connor, an assistant professor at the University of Massachusetts, Amherst, and one of his graduate students, Su Lin Blodgett, looked at the use of language on Twitter. Using demographic filtering, the researchers collected 59.2 million tweets with a high probability of containing African-American slang or vernacular. They then tested several natural-language processing tools on this data set to see how they would treat the statements. They found that one popular tool classified these posts as Danish with a high level of confidence.

"If you analyze Twitter for people's opinions on a politician and you're not even considering what African-Americans are saying or young adults are saying, that seems problematic," O'Connor says.

The pair also tested several popular machine-learning-based APIs that analyze text for meaning and sentiment, and they found that these systems struggled, too. "If you purchase a sentiment analyzer from some company, you don't even know what biases it has in it," O'Connor says.

He says the problem extends to any system that uses language, including search engines.

The issue of unfairness stemming from the use of AI algorithms is gaining attention as these algorithms are used more widely. One example is a proprietary algorithm called Compass, which is used to decide whether prison inmates should be granted parole. The workings of the algorithm are unknown, but research suggests it is biased against black inmates.

Some experts say that the problem may be affecting a growing number of decisions in finance, health care, and education. Shared Goel, an assistant professor at Stanford University who studies algorithmic fairness and public policy, says the issue is not always straightforward. He notes that it can be overly simplistic to call algorithms biased: they may work entirely as intended, making predictions that are accurate, and simply reflect broader social biases. "It's better to describe what an algorithm is doing, the reason it's doing it, and then to decide if that's what we want it to do," Goel says.

—Will Knight

TO MARKET

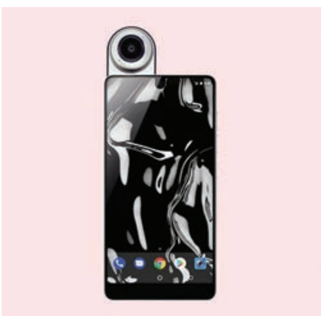
Essential Phone

Android smartphone

COMPANY:
Essential

PRICE:
$699

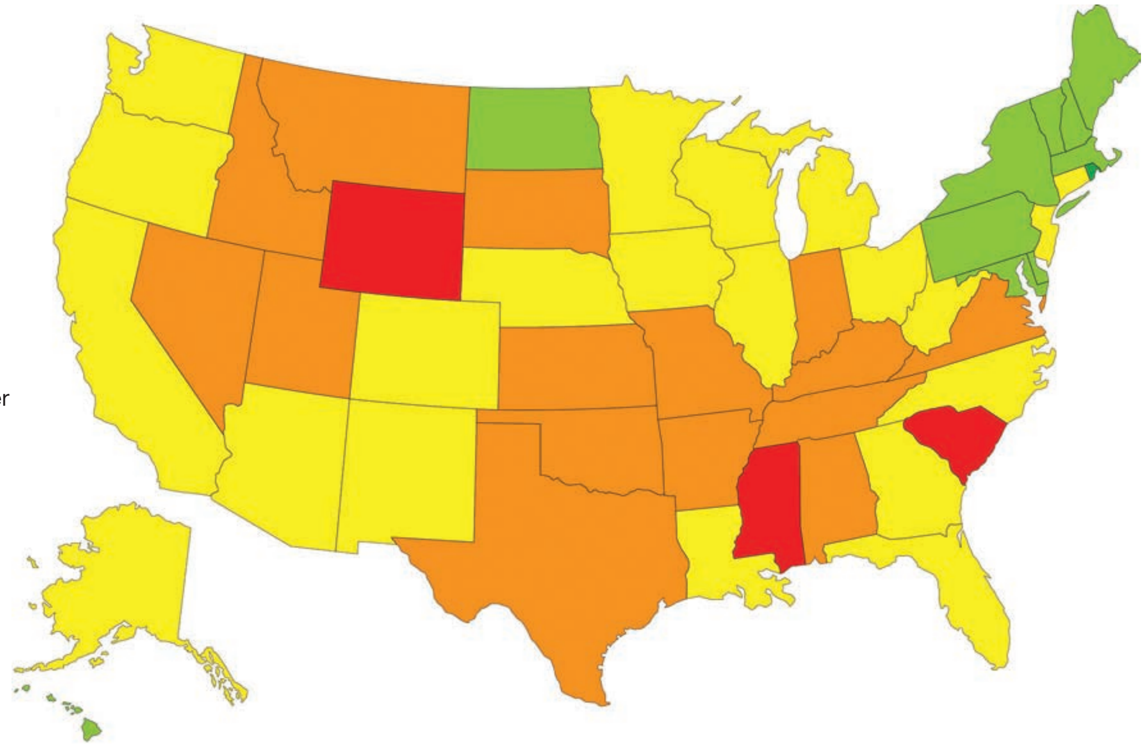
AVAILABILITY:
Now



ESSENTIAL

Many smartphones are odes to metal and glass. This one, from Andy Rubin, the creator of Android, has a titanium body and a ceramic back (besides looking good, this should hold up to inevitable drops). It's also got two little magnetic connectors on the back to snap accessories on and off, so you can add more features over time, such as a 360° camera that the company is selling alongside the phone. Watching videos on the Essential Phone is a lot of fun, as its display is fantastic and bright. I was surprised that its built-in speaker—which I usually eschew for earbuds—worked well even at top volume. But is this phone really "essential"? For most of us, not so much. *—Rachel Metz*

Upfront



The Cancer Vaccine That Too Many People Ignore

The potentially life-saving HPV vaccine has been around for more than a decade. So why isn't everyone getting it?

Mandi Price was a seemingly healthy 24-year-old college student when, during a regular Pap smear, her gynecologist found abnormal cells in her cervix. It was stage 2 cervical cancer.

Even more devastating was that her cancer was preventable. Doctors detected a strain of human papillomavirus, the most common sexually transmitted infection in the U.S., in Price's cancer cells. That strain of HPV is targeted by a vaccine called Gardasil. But Price never got the vaccine. Her primary care doctor in Washington state didn't recommend it when she was a teenager. Had she received it before becoming infected with HPV, she might not have gotten cancer.

Price dropped out of school to get treatment. She needed surgery to remove the tumor from her cervix; then she underwent chemotherapy and radiation to kill any remaining cancerous tissue. At her one-year follow-up, doctors found that the cancer had spread. She endured chemotherapy for another six months. Now 29, Price is in remission and is working in Los Angeles. "Most of my 20s comprised being in a hospital. It was isolating," she says.

Merck's Gardasil vaccine was considered a breakthrough when it was approved by the U.S. Food and Drug Administration in June 2006. It was the first vaccine to protect against several cancers. But more than a decade after the vaccine came out, rates of use in many places in the U.S., especially in the South, Midwest, and Appalachian states, still remain much lower than rates for other childhood vaccines—too low to stop transmission of the most dangerous HPV strains.

In 2016, only about 50 percent of girls and 38 percent of boys had all three doses of the HPV vaccine needed for full protection, according to data released recently by the U.S. Centers for Disease Control and Prevention. HPV causes about 32,000 cancers every year, with cervical cancer the most common for women and oral cancers the most frequent in men.

Electra Paskett, a cancer epidemiologist at Ohio State University, says she is still surprised that the vaccine's uptake has been so slow. "It's crazy that there's not a

SOURCE: CDC

line around the corner. If we said we have a vaccine for breast cancer, we'd be vaccinating day and night," she says.

The problem the vaccine has faced is its link to a taboo in American culture: sexual activity among teenagers. About one in four people in the U.S., including teens, are currently infected with HPV. But many health-care providers hesitate to recommend the vaccine.

State vaccination rates were as high as 73 percent among girls in Rhode Island and as low as 31 percent in South Carolina for all three doses in 2016. Among boys, Wyoming had the lowest rate, with only 20 percent getting the full round of shots. Overall, teens living in major metropolitan areas were far more likely to get the vaccine than those living in rural areas.

In some states with low vaccination rates, the rates of HPV-caused cancers are the among the highest. In Mississippi, only about 34 percent of girls and 25 percent of boys get all required doses of the vaccine. The state also has one of the highest rates of HPV-related cervical cancer in the country. Wyoming tells a similar story, with high rates of HPV-associated cancers in both men and women.

HPV vaccination for boys is especially lagging in some areas. Paskett, who has studied cancer in Appalachia, say there's a perception that HPV only causes cancers in women. "A lot of parents don't know that boys should be vaccinated," she says.

A 2015 study found that a quarter of the 776 pediatricians and family physicians surveyed do not strongly endorse the HPV vaccine. A third of the doctors said that having to talk about a sexually transmitted infection makes them uncomfortable.

"We don't usually explain to patients how they get hepatitis or meningitis," says Nneka Holder, associate professor of adolescent medicine at the University of Mississippi Medical Center. "So why should HPV be different?" Instead, she says, health-care providers should focus on the cancer prevention aspect of the vaccine, rather than on how HPV is spread.

Since the vaccine is just over 10 years old, it's too early to know how many cases of cancer it has prevented. But clinical trials have shown that the vaccine provides nearly 100 percent protection against cervical infections caused by some strains of HPV. These infections have fallen by 64 percent among teen girls in the U.S. since the vaccine was introduced. Clinical trials of the HPV vaccine have also shown it's safe for both boys and girls.

These benefits have led Virginia, Rhode Island, and Washington, D.C., to adopt public school mandates for HPV vaccination. But some parents are still uncomfortable about the HPV vaccine's association with sex and think their children don't need it because they're not sexually active.

Aimee Gardiner, director of a group called Rhode Island Against Mandated HPV Vaccine, says she doesn't see HPV as the "epidemic" she thinks the CDC has made it out to be. "For me, the risk of developing a cancer from any HPV is so insignificantly small that I do not feel like the vaccine is a necessity," she says.

It's true that for most people, the immune system clears the virus from their bodies naturally. But for a small number of people, HPV persists and can turn cancerous. For those patients, like Price, the result can be a major ordeal, not to mention much more expensive than a vaccine that costs about $150 per dose.

"I am a huge proponent of it," she says. "If you had the chance to prevent cancer in your son or daughter, why wouldn't you do that?" *—Emily Mullin*

"We don't usually explain to patients how they get hepatitis or meningitis."

QUOTED

"You can't have a data set that includes the whole world."

—Yibiao Zhao, cofounder of iSee, on the importance of giving self-driving cars a kind of common sense and the ability to quickly deal with new situations.

"It generates really interesting-looking cats."

—Douglas Eck, a research scientist at Google, on Sketch-RNN, a neural network that can generate its own drawings.

"There is no basis for saying our findings are impossible."

—Saswati Chatterjee, scientific founder of Homology Medicines, on critics of the company's claim that it can repair human genes with viruses, a potential improvement over the gene-editing tool CRISPR.

BY THE NUMBERS

1,101 miles

Distance that a Proterra electric bus traveled on a single charge—a world record, albeit at 15 mph.

12 inches

Distance over which a startup called Pi claims its wireless charger can send power to a mobile device by inductive charging.

1 trillion

The number of connected devices that ARM thinks its chips could enable by 2035.

52 percent

The proportion of people on the planet who still lack Internet access, according to a UN report.

20

According to Symantec, the number of cases across the U.S., Turkey, and Switzerland in which criminals gained operational access to energy facilities—in theory, giving them the ability to remotely turn off devices like circuit breakers.

Upfront

Potential Carbon Capture Game Changer Is Near

If it works as expected, the Net Power natural-gas demonstration plant will capture carbon at nearly no cost.

On a small lot between Houston and the Gulf Coast, in an industrial zone packed with petrochemical factories and gas pipelines, a little-known company is finalizing construction of a demonstration power plant that could represent a genuine energy breakthrough. If it works as expected, Net Power's $140 million, 50-megawatt natural-gas plant will capture effectively all of the carbon dioxide it produces, without significantly higher costs, in part by relying on the greenhouse gas itself to crank the turbine that generates electricity. The technology could enable a new generation of plants that provide clean power, without the development risks of nuclear, the geographic restrictions of hydroelectric, or the intermittency issues of solar and wind.

Net Power's maze of tubes, tanks, compressors, and pumps uses what is known as the Allam Cycle. It eliminates the steam cycle by replacing water with supercritical carbon dioxide. In this state, achieved under high heat and pressure, carbon dioxide takes on the properties of both a liquid and a gas. The process was primarily developed by the British chemical engineer and inventor Rodney Allam, now a partner and chief technologist at the technology investment and development firm 8 Rivers Capital in Durham, North Carolina. Net Power is a collaboration between 8 Rivers, plant operator Exelon Generation, and energy construction firm CB&I.

Eventually, Net Power expects to produce electricity for around $42 per megawatt-hour, on par with combined-cycle natural gas without carbon capture. But on top of all that, the company can also sell several by-products, including carbon dioxide. Taken together, those could effectively push energy production costs down to around $20 per megawatt-hour (theoretically, even as low as $9 per megawatt-hour). Local, state, or federal clean-energy policies—such as carbon taxes, cap-and-trade systems, and emissions standards—could further improve the economics.

Net Power has already begun conversations and explored potential sites for its first commercial plant, which it hopes will come online as early as 2021. "If it plays out as advertised, it could be an actual game changer," says Jesse Jenkins, a researcher at the MIT Energy Initiative. *—James Temple*

TO MARKET

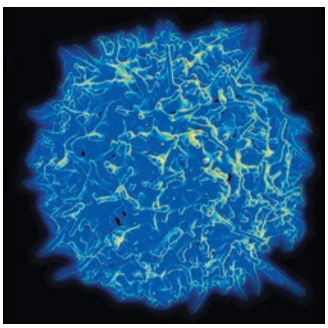
Kymriah

Gene therapy for cancer

COMPANY:
Novartis

PRICE:
$475,000

AVAILABILITY:
Now



A revolutionary cancer therapy that uses genetically engineered immune cells was approved in August by the U.S. Food and Drug Administration. Kymriah, which the FDA calls the "first gene therapy" in the U.S., is designed to treat an often lethal type of childhood blood and bone marrow cancer. "We're entering a new frontier in medical innovation with the ability to reprogram a patient's own cells to attack a deadly cancer," said FDA commissioner Scott Gottlieb in a statement. It costs $475,000, which David Mitchell, founder of the advocacy group Patients for Affordable Drugs, calls "excessive." Novartis says there will be no charge if a patient does not respond within one month. *—Emily Mullin*

NET POWER; NATIONAL CANCER INSTITUTE

Upfront

China's Ambitious Push for Geoengineering Research

Backed by $3 million in federal funds, Chinese scientists are assessing how geoengineering would affect agriculture, glaciers, sea levels, and more.

During the last three years, China has assembled one of the largest federally funded geoengineering research programs in the world, marking another area where it's forging ahead of other nations on climate matters.

The approximately $3 million program, funded by the Ministry of Science and Technology, incorporates around 15 faculty members and 40 students across three institutions. The researchers are assessing the impact of using technology to alter the climate and exploring related governance issues. The effort explicitly does not include technology development or outdoor experiments, in contrast to emerging U.S. research programs at Harvard and the University of Washington.

"They don't want to be seen as the bad guys, so there's a reluctance to do that among some groups," says John Moore, a British glaciologist and climate modeler who is overseeing the program.

Geoengineering is a blanket term for a number of proposed methods for counteracting climate change. Among other approaches, scientists have explored the possibility of spraying particles into the stratosphere to scatter sunlight. Another idea is making coastal clouds more reflective. It's generally believed such methods could offset temperature increases, but there are considerable concerns about potential environmental side effects, the tricky political challenges they raise, and the ethics of deploying a technology that could alter climate on a global scale.

Given these challenges and the rising threat of climate change, a growing number of scientists say there should be far more research and debate on all these issues. And since geoengineering would generally affect all countries, regardless of which ones deploy it, the more nations that take part the better, says Douglas MacMartin, a senior research associate in mechanical and aerospace engineering at Cornell University, who has advised on the Chinese program.

Because China is increasingly influential on climate issues, the broader significance of the geoengineering program may be the international example that it sets, says Janos Pasztor, executive director of the Carnegie Climate Geoengineering Governance Initiative.

Notably, it could compel other nations to make similar investments in exploring the regional impacts and policy implications of geoengineering, or at least to engage on the subject. In fact, the program has already taken steps to incorporate poor nations like the Philippines and Bangladesh into discussions on the issue; this past summer it hosted a workshop on geoengineering in the developing world.

But are there any risks if China, with its mixed history on human rights and its lack of democratic institutions, establishes itself as a scientific leader in a field with the power to alter the entire globe, for better or worse?

To the degree that the science is openly published and there's a lot left to learn, "it doesn't matter which country understands first," Pasztor says.

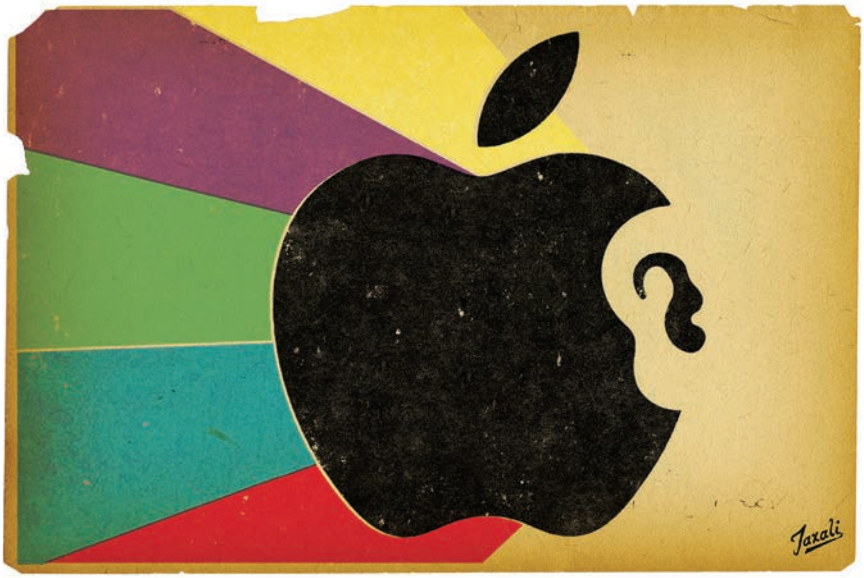
But over the long term, there could be risks if any single nation dominates the research on this issue, because it could also come to dominate the debate on how, when, and whether to ultimately deploy such technology, MacMartin says.

"It is essential for the U.S. to continue to have a seat at the table in any decision that affects the entire planet," he says.

—James Temple

TOMI UM

Upfront



Apple Wireless Earbuds Could Double as Hearing Aids

This app that pairs with AirPods promises to help people with hearing loss.

What if a hearing aid could be replaced with a pair of wireless earbuds and a smartphone app?

A Swiss startup is trying to make this a reality with an app called Fennex, recently released for the iPhone, that works with Apple's $159 AirPods wireless earbuds. Alex Mari, CEO of the startup of the same name, says that he chose Apple's devices and mobile platform for the app in part because of their popularity but also because he thinks an Android phone would result in more latency when processing sound.

The app is still in its earliest days; it's currently free, though Fennex may eventually charge for certain features. Mari says today's version functions like a "cheap hearing aid": it simply tests your hearing in each ear and uses those results to act as a personalized, adjustable amplifier. If you're having trouble hearing in a class, for instance, you could place your phone near the lectern while you're sitting a few rows back and listening in on a pair of AirPods.

But upgrades are coming, Mari says: the app is slated to gain features that will help reduce unwanted noise and feedback. And beyond helping people who just want to hear better in some situations, the software could eventually work with Apple's hardware to serve as a viable alternative to a regular hearing aid for people who have moderate hearing loss, he believes.

"We want to get as close as we can to hearing aid technology," he says.

Fennex is latching onto a broader trend in using smartphones and earbuds to augment hearing, both for people with hearing loss and for those who simply want to adjust how they hear. Already, there are similar apps that work with earbuds and smartphones, like Petralex, as well as specialized earbuds that work with their own smartphone apps, like Doppler Labs' Here One. Unlike hearing aids, which can cost thousands of dollars for a pair, these so-called hearables may cost up to a few hundred dollars on top of the price of a smartphone.

Fennex claims to have the only app designed for AirPods specifically. And since Apple is clearly moving away from the traditional headphone jack—it cut it out of the iPhones released last year and included just its proprietary Lightning connector for charging—it is possible that in the coming years AirPods will become a lot more common.

Larry Humes, a distinguished professor of speech and hearing sciences at Indiana University Bloomington, is optimistic that something like Fennex could take the place of a traditional hearing aid for those with mild to moderate hearing loss. He thinks the recent passage of legislation that orders the FDA to create a new class of over-the-counter hearing aids could help, too, as he expects it will lead to a range of hearing-related products that people can get without needing to visit a doctor.

However, as Mari knows, it's clearly a risk to focus on making software for one pair of earbuds, since Fennex can't control what Apple does with its hardware or the access it gives to developers who want to develop software that works with it.

There's also the issue of hearing delays. Fennex works by using the AirPods' microphones to record sounds in the world around the wearer, after which it sends the audio to the iPhone app for processing and then back to the earbuds. The delay, for now, is 130 milliseconds, which might be fine for listening but is noticeable if you're trying to engage in a conversation. —*Rachel Metz*

GARY TAXALI

The App That Boomed in China (but Bombed in the U.S.)

China's WeChat struggles for an audience overseas.

Some of America's most formidable technology companies have gone to China and found that their superpowers seemed to vanish. Uber, Amazon, Apple—all were humbled by the Chinese market. It may be tempting to blame Chinese government restrictions, but that wouldn't explain why the reverse is also true: China's superstar companies struggle to make it in the U.S.

There's no better example than Tencent's WeChat, a mobile messaging and payment app with over 900 million monthly active users. Foreigners who visit China are awestruck by the complete dominance of this app, which people use for everything from sending messages to hailing taxis to buying real estate.

In 2013, Tencent announced that it aimed to bring WeChat to America. There were already messaging apps in the U.S. market, but none had taken the country by storm, and there seemed to be room for WeChat to shake things up.

It didn't happen. But why? It's no secret that China has a heavily censored Internet and that WeChat is a heavily censored product. This can make international expansion confusing at best: sensitive content on international accounts might be blocked in China. But censorship doesn't appear to be the main obstacle for WeChat in the U.S. Rather, WeChat faces the same network-effect challenges that American companies encounter in China. Facebook is currently blocked there, a factor that certainly contributed to WeChat's success. Now, if Facebook were to make it in, it would find that everyone is already on WeChat. The two products are different, of course, but WeChat works so well in China precisely because so many Chinese people are on it. Users' favorite brands and celebrities are there, as are friends, family, and coworkers. Facebook would have a nearly impossible time replicating that kind of network.

Network effects are only part of the story. WeChat was designed for the Chinese market. Connie Chan, a partner at Andreessen Horowitz, says that when WeChat was launched in 2011, Chinese people had no universal way to communicate. E-mail penetration was low. SMS and voice plans were relatively expensive, and SMS spam was a serious problem. By the end of 2015, more than half of China's population was online, with 90 percent accessing the Web by smartphone.

This was very different from the environment that Tencent encountered in the U.S. in 2013. People already had Facebook, WhatsApp, and iMessage, as well as e-mail and many other ways to communicate. Chan explains, "There was less of a strong need to have this one unifying platform for everyone."

Companies like Tencent "want to be compared to Facebook, Google, and Amazon," Chan says. "They want to be in that same conversation." She notes that the market cap for Tencent is over $390 billion: "From that perspective, they have the capital to go overseas and purchase things, or invest in things, or try more experiments." *—Emily Parker*

TO MARKET

GuardHat

Smart hard hat

COMPANY:
GuardHat

PRICE:
N/A

AVAILABILITY:
2018

NISHANT CHOKSI; GUARDHAT

You're a construction worker and you're exposed to carbon monoxide, or you fall into a hole when nobody's around. Normally that means you're in deep trouble. But what if sensors on your hard hat could monitor the air quality in real time, or monitor your location and alert people nearby? That's the idea behind the GuardHat, a sensor-laden hard hat from a startup of the same name. Gerrit Reepmeyer, the company's cofounder, says the system is currently being tested by three oil and gas companies in North America and Europe, with more tests by mining operations on the way. The flip side for workers: wherever you go, your supervisor knows about it. *—Timothy Maher*

Upfront

The System Behind Bitcoin Is Easing the Plight of Refugees

Finland's digital money system for asylum seekers shows what blockchain technology can offer the unbanked.

For a refugee in a new country, identity, at least in the official sense, can be among the hardest things to recover. And without an official ID it is nearly impossible to advance in society.

Finland, which like many European nations has recently seen a large influx of asylum seekers, is using a cryptographic ledger, or blockchain, to help them get on their feet faster.

For two years the Finnish Immigration Service has been giving asylum seekers who don't have bank accounts prepaid MasterCards instead of the traditional cash disbursements, and today the program has several thousand active cardholders. Developed by the Helsinki-based startup Moni, the card is also linked to a unique digital identity stored on a blockchain, the same technology that underpins the digital currency Bitcoin.

Bitcoin has demonstrated how blockchain technology can be used to transmit value between people, with no need for corporate middlemen. Central to the technology is a software protocol that creates a permanent record of every Bitcoin transaction. Anyone can access this record, called the blockchain, by downloading the Bitcoin software. Computers running the software all over the world maintain the blockchain, and use it to verify new transactions.

Blockchains are a promising avenue for opening new financial opportunities to people who don't have access to modern financial services. Besides eliminating the need for a traditional financial institution to mediate transactions, they provide a way to create and securely store a digital form of identification that can't be corrupted and is easily accessible from anywhere.

In Finland, a Moni card can help address several challenges facing asylum seekers, says Jouko Salonen, director of the Finnish Immigration Service. A Moni account functions like a bank account. People can use their accounts to buy things, pay bills, and even receive direct deposits from employers. Meanwhile, every transaction is recorded in a public, virtually incorruptible database maintained by a decentralized global network of computers.

The technology helps unbanked asylum seekers because what typically keeps them from getting bank accounts and jobs is that they're missing a form of strongly authenticated identity, says Salonen. He adds, "We have found a way to solve that."

Moni's technology uses one of a number of public blockchains as the means of transferring value—but in a way that to the users seems like using a debit card. A cardholder can pay for things at MasterCard terminals, or enter a number into a Web form to make payments online.

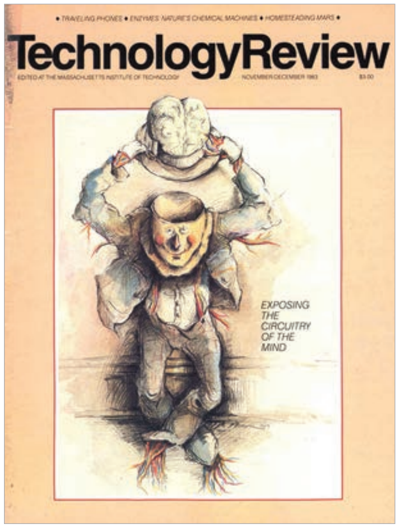
Antti Pennanen, Moni's founder and CEO, likens blockchain to the early Internet, which was accessible only to a select few with the technical wherewithal to use it. His says Moni's technology is somewhat analogous to a modem, which made the Internet usable for more people.

Pennanen says word of Moni has spread to refugee camps throughout Europe. He expects substantial demand among those displaced communities once the service is available in other countries.

—Mike Orcutt

34 YEARS AGO

Exciting, but Not Very Deep



A debate centers on whether expert systems enable computers to really think. Nobel laureate Herbert Simon, an AI pioneer, believes they do. "Intelligence has to do with the ability to respond appropriately to complex situations," he says. "Every time we write a computer program to do that, particularly if it's a fairly general program, I find it quite natural to speak of the computer as exhibiting intelligence." Marvin Minsky of MIT thinks the present expert systems have gone as far as they can go, and AI researchers are going to have to go back to basics, or "First Principles." "These programs are exciting but most of them are not very deep," he says. "You don't see researchers working on the problem of commonsense reasoning, for instance. There is no program around today that will tell the difference between a dish and a cup."

Excerpted from "The Practical Face of Artificial Intelligence," by Stanford professor Joel N. Shurkin in the November 1983 issue of Technology Review.

Q+A

Fei-Fei Li

As the director of Stanford's AI Lab and now as a chief scientist of Google Cloud, Fei-Fei Li is helping to spur the AI revolution. But it's a revolution that needs to include more people. She spoke with *MIT Technology Review* senior editor Will Knight about why everyone benefits if we emphasize the human side of the technology.

Why did you join Google?

Researching cutting-edge AI is very satisfying and rewarding, but we're seeing this great awakening, a great moment in history. For me it's very important to think about AI's impact in the world, and one of the most important missions is to democratize this technology. The cloud is this gigantic computing vehicle that delivers computing services to every single industry.

What have you learned so far?

We need to be much more human-centered. If you look at where we are in AI, I would say it's the great triumph of pattern recognition. It is very task-focused, it lacks contextual awareness, and it lacks the kind of flexible learning that humans have. We also want to make technology that makes humans' lives better, our world safer, our lives more productive and better. All this requires a layer of human-level communication and collaboration.

How can we make AI more human-centered?

There's a great phrase, written in the '70s: "the definition of today's AI is a machine that can make a perfect chess move while the room is on fire." It really speaks to the limitations of AI. In the next wave of AI research, if we want to make more helpful and useful machines, we've got to bring back the contextual understanding. We've got to bring knowledge abstraction and reasoning. These are all the most important steps.

At Stanford you created Visual Genome, a database of images that are extensively labeled so they can be used for AI systems. Is this interplay of vision and language necessary for the next leap forward?

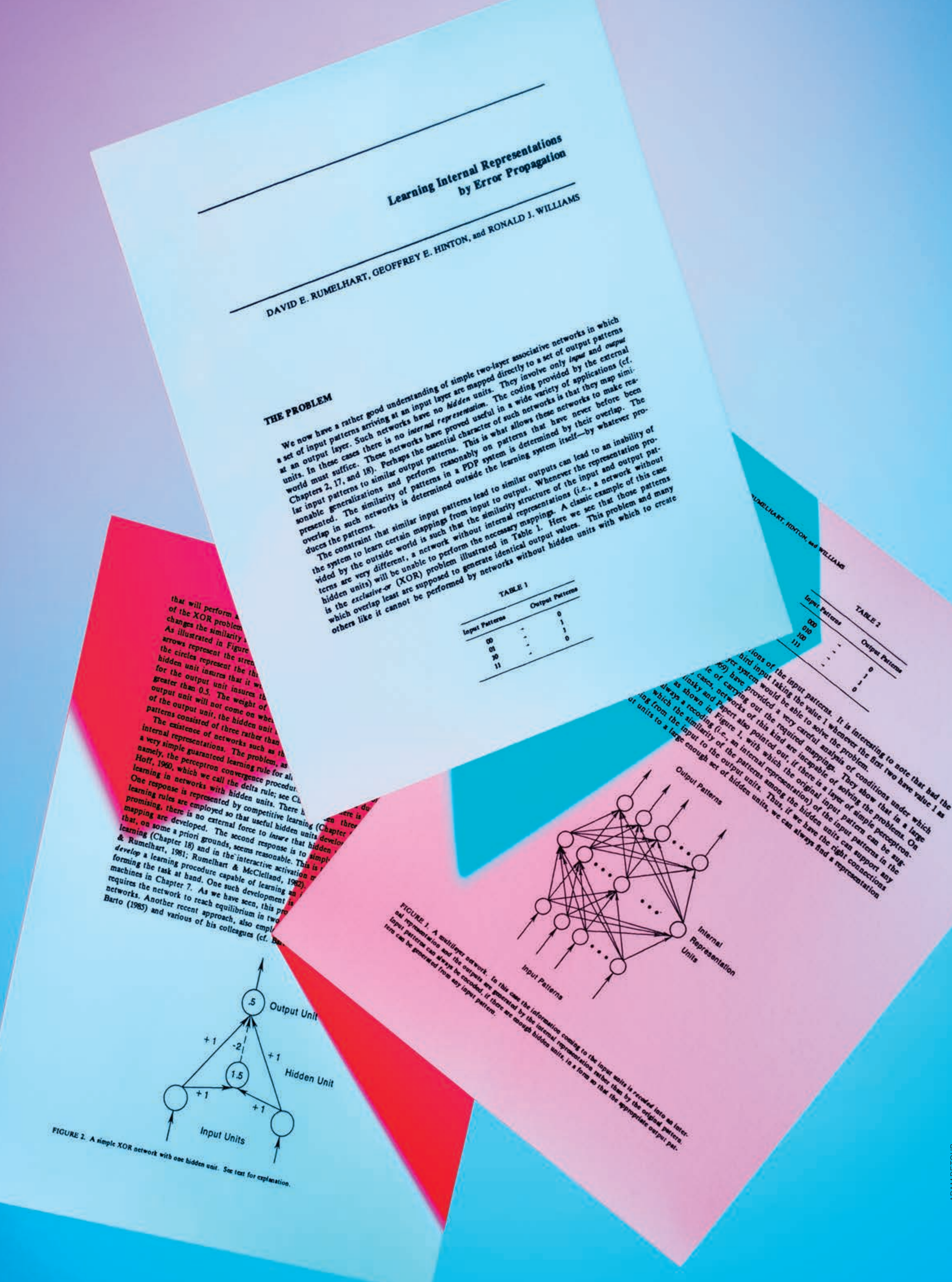
Absolutely. Vision is a cornerstone of intelligence, and language understanding is a cornerstone of intelligence. What makes humans unique is that evolution gave us the most incredible and sophisticated vision system, motor system, and language system, and they all work together. Visual Genome is exactly the kind of project that's pushing the boundaries of language understanding and visual understanding. And eventually we're going to connect with the world of robotics as well.

You've talked about the need to have more women involved in AI. Why?

More jobs will be related to artificial intelligence, so we need a huge workforce, and we need a more inclusive base. That's an economic argument. There are also tons of studies that have shown that when a diverse group of workers come together, the solutions they find in their work are more innovative and more creative. That drives innovation. But it's also moral and ethical.

When you are making a technology this pervasive and this important for humanity, you want it to carry the values of the entire humanity, and serve the needs of the entire humanity. If the developers of this technology do not represent all walks of life, it is very likely that this will be a biased technology. I say this as a technologist, a researcher, and a mother. And we need to be speaking about this clearly and loudly.

BLAKE FARRINGTON


Learning Internal Representations
by Error Propagation
DAVID E. RUMELHART, GEOFFREY E. HINTON, and RONALD J. WILLIAMS
THE PROBLEM
We now have a rather good understanding of simple two-layer associative networks in which a set of input patterns arriving at an input layer are mapped directly to a set of output patterns at an output layer. Such networks have no hidden units. They involve only input and output units. In these cases there is no internal representation. The coding provided by the external world must suffice. These networks have proved useful in a wide variety of applications (cf. Chapters 2, 17, and 18). Perhaps the essential character of such networks is that they map similar input patterns to similar output patterns. This is what allows these networks to make reasonable generalizations and perform reasonably on patterns that have never before been presented. The similarity of patterns in a PDP system is determined by their overlap. The overlap in such networks is determined outside the learning system itself—by whatever produces the patterns.
The constraint that similar input patterns lead to similar outputs can lead to an inability of the system to learn certain mappings from input to output. Whenever the representation provided by the outside world is such that the similarity structure of the input and output patterns are very different, a network without internal representations (i.e., a network without hidden units) will be unable to perform the necessary mappings. A classic example of this case is the exclusive-or (XOR) problem illustrated in Table 1. Here we see that those patterns which overlap least are supposed to generate identical output values. This problem and many others like it cannot be performed by networks without hidden units with which to create
TABLE 1
Input Patterns → Output Patterns
00 → 0
01 → 1
10 → 1
11 → 0
Output Patterns
Internal Representation Units
Input Patterns
FIGURE 1. A multilayer network. In this case the information coming to the input units is recoded into an internal representation and the outputs are generated by the internal representation rather than by the original pattern. Input patterns can always be encoded, if there are enough hidden units, in a form so that the appropriate output pattern can be generated from any input pattern.
.5
Output Unit
+1
-2
+1
1.5
Hidden Unit
+1
+1
Input Units
FIGURE 2. A simple XOR network with one hidden unit. See text for explanation.

ADAM DETOUR

Is AI Riding a One-Trick Pony?

Self-driving cars, computers that win Go championships, and just about every other AI advance you've heard of all depend on a breakthrough that's three decades old. Keeping up the pace of progress will require confronting AI's serious limitations.

By James Somers

This publication from the mid-1980s showed how to train a neural network with many layers. It set the stage for this decade's progress in AI.

I'm standing in what is soon to be the center of the world, or is perhaps just a very large room on the seventh floor of a gleaming tower in downtown Toronto. Showing me around is Jordan Jacobs, who cofounded this place: the nascent Vector Institute, which opens its doors this fall and which is aiming to become the global epicenter of artificial intelligence.

We're in Toronto because Geoffrey Hinton is in Toronto, and Hinton is the father of "deep learning," the technique behind the current excitement about AI. "In 30 years we're going to look back and say Geoff is Einstein—of AI, deep learning, the thing that we're calling AI," Jacobs says. Of the AI researchers at the top of the field of deep learning, Hinton has more citations than the next three combined. His students and postdocs have gone on to run the AI labs at Apple, Facebook, and OpenAI; Hinton himself is a lead scientist on the Google Brain AI team. In fact, nearly every achievement in the last decade of AI—in translation, speech recognition, image recognition, and game playing—traces in some way back to Hinton's work.

The Vector Institute, this monument to the ascent of Hinton's ideas, is a research center where companies from around the U.S. and Canada—like Google, and Uber, and Nvidia—will sponsor efforts to commercialize AI technologies. Money has poured in faster than Jacobs could ask for it; two of his cofounders surveyed companies in the Toronto area, and the demand for AI experts ended up being 10 times what Canada produces every year. Vector is in a sense ground zero for the now-worldwide attempt to mobilize around deep learning: to cash in on the technique, to teach it, to refine and apply it. Data centers are being built, towers are being filled with startups, a whole generation of students is going into the field.

The impression you get standing on the Vector floor, bare and echoey and about to be filled, is that you're at the beginning of something. But the peculiar thing about deep learning is just how old its key ideas are. Hinton's breakthrough paper, with colleagues David Rumelhart and Ronald Williams, was published in 1986. The paper elaborated on a technique called backpropagation, or backprop for short. Backprop, in the words of Jon Cohen, a computational psychologist at Princeton, is "what all of deep learning is based on—literally everything."

When you boil it down, AI today is deep learning, and deep learning is backprop—which is amazing, considering that backprop is more than 30 years old. It's worth understanding how that happened—how a technique could lie in wait for so long and then cause such an explosion—because once you understand the story of backprop, you'll start to understand the current moment in AI, and in particular the fact that maybe we're not actually at the beginning of a revolution. Maybe we're at the end of one.

Vindication

The walk from the Vector Institute to Hinton's office at Google, where he spends most of his time (he is now an emeritus professor at the University of Toronto), is a kind of living advertisement for the city, at least in the summertime. You can understand why Hinton, who is originally from the U.K., moved here in the 1980s after working at Carnegie Mellon University in Pittsburgh.

When you step outside, even downtown near the financial district, you feel as though you've actually gone into nature. It's the smell, I think: wet loam in the air. Toronto was built on top of forested ravines, and it's said to be "a city within a park"; as it's been urbanized, the local government has set strict restrictions to maintain the tree canopy. As you're flying in, the outer parts of the city look almost cartoonishly lush.

Toronto is the fourth-largest city in North America (after Mexico City, New York, and L.A.), and its most diverse: more than half the population was born outside Canada. You can see that walking around. The crowd in the tech corridor looks less San Francisco—young white guys in hoodies—and more international. There's free health care and good public schools,

Maybe we're not actually at the beginning of a revolution.

the people are friendly, and the political order is relatively left-leaning and stable; and this stuff draws people like Hinton, who says he left the U.S. because of the Iran-Contra affair. It's one of the first things we talk about when I go to meet him, just before lunch.

"Most people at CMU thought it was perfectly reasonable for the U.S. to invade Nicaragua," he says. "They somehow thought they owned it." He tells me that he had a big breakthrough recently on a project: "getting a very good junior engineer who's working with me," a woman named Sara Sabour. Sabour is Iranian, and she was refused a visa to work in the United States. Google's Toronto office scooped her up.

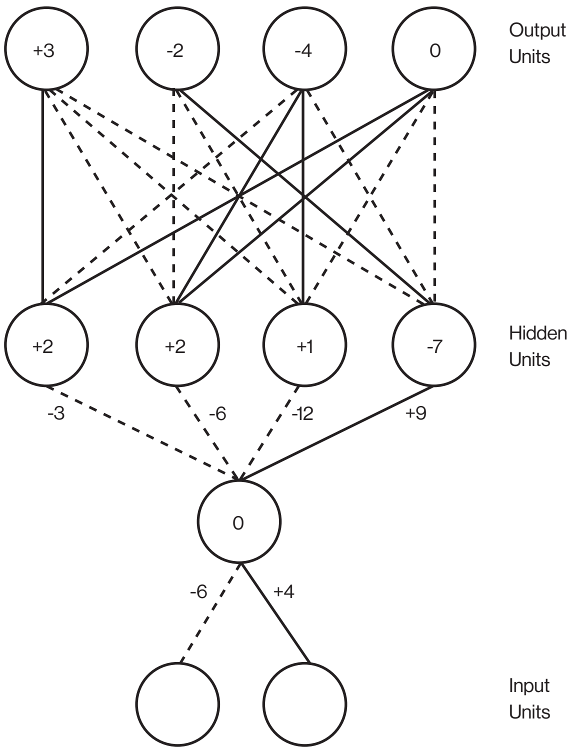
Hinton, who is 69 years old, has the kind, lean, English-looking face of the Big Friendly Giant, with a thin mouth, big ears, and a proud nose. He was born in Wimbledon, England, and sounds, when he talks, like the narrator of a children's book about science: curious, engaging, eager to explain things. He's funny, and a bit of a showman. He stands the whole time we talk, because, as it turns out, sitting is too painful. "I sat down in June of 2005 and it was a mistake," he tells me, letting the bizarre line land before explaining that a disc in his back gives him trouble. It means he can't fly, and earlier that day he'd had to bring a contraption that looked like a surfboard to the dentist's office so he could lie on it while having a cracked tooth root examined.

In the 1980s Hinton was, as he is now, an expert on neural networks, a much-simplified model of the network of neurons and synapses in our brains. However, at that time it had been firmly decided that neural networks were a dead end in AI research. Although the earliest neural net, the Perceptron, which began to be developed in the 1950s, had been hailed as a first step toward human-level machine intelligence, a 1969 book by MIT's Marvin Minsky and Seymour Papert, called *Perceptrons*, proved mathematically that such networks could perform only the most basic functions. These networks had just two layers of neurons, an input layer and an output layer. Nets with more layers between the input and output neurons could in theory solve a great variety of problems, but nobody knew how to train them, and so in practice they were useless. Except for a few holdouts like Hinton, *Perceptrons* caused most people to give up on neural nets entirely.

Hinton's breakthrough, in 1986, was to show that backpropagation could train a deep neural net, meaning one with more than two or three layers. But it took another 26 years before increasing computational power made good on the discovery. A 2012 paper by Hinton and two of his Toronto students showed that deep neural nets, trained using backpropagation, beat state-of-the-art systems in image recognition. "Deep learning" took off. To the outside world, AI seemed to wake up overnight. For Hinton, it was a payoff long overdue.

Reality distortion field

A neural net is usually drawn like a club sandwich, with layers stacked one atop the other. The layers contain artificial neurons, which are dumb little computational units that get excited—the way a real neuron gets excited—and pass that excitement on to the other neurons they're connected to. A neuron's excitement is represented by a number, like 0.13 or 32.39, that says just how excited it is. And there's another crucial number, on each of the connections between two neurons, that determines how much excitement should get passed from one to the other. That number is meant to model the strength



A diagram from seminal work on "error propagation" by Hinton, David Rumelhart, and Ronald Williams.

of the synapses between neurons in the brain. When the number is higher, it means the connection is stronger, so more of the one's excitement flows to the other.

One of the most successful applications of deep neural nets is in image recognition—as in the memorable scene in HBO's *Silicon Valley* where the team builds a program that can tell whether there's a hot dog in a picture. Programs like that actually exist, and they wouldn't have been possible a decade ago. To get them to work, the first step is to get a picture. Let's say, for simplicity, it's a small black-and-white image that's 100 pixels wide and 100 pixels tall. You feed this image to your neural net by setting the excitement of each simulated neuron in the input layer so that it's equal to the brightness of each pixel. That's the bottom layer of the club sandwich: 10,000 neurons (100x100) representing the brightness of every pixel in the image.

You then connect this big layer of neurons to another big layer of neurons above it, say a few thousand, and these in turn to another layer of another few thousand neurons, and so on for a few layers. Finally, in the topmost layer of the sandwich, the output layer, you have just two neurons—one representing "hot dog" and the other representing "not hot dog." The idea is to teach the neural net to excite only the first of those neurons if there's a hot dog in the picture, and only the second if there isn't. Backpropagation—the technique that Hinton has built his career upon—is the method for doing this.

Backprop is remarkably simple, though it works best with huge amounts of data. That's why big data is so important in AI—why Facebook and Google are so hungry for it, and why the Vector Institute decided to set up shop down the street from four of Canada's largest hospitals and develop data partnerships with them.

In this case, the data takes the form of millions of pictures, some with hot dogs and some without; the trick is that these pictures are labeled as to which have hot dogs. When you first create your neural net, the connections between neurons might have random weights—random numbers that say how much excitement to pass along each connection. It's as if the synapses of the brain haven't been tuned yet. The goal of backprop is to change those weights so that they make the network work: so that when you pass in an image of a hot dog to the lowest layer, the topmost layer's "hot dog" neuron ends up getting excited.

Suppose you take your first training image, and it's a picture of a piano. You convert the pixel intensities of the 100x100 picture into 10,000 numbers, one for each neuron in the bottom layer of the network. As the excitement spreads up the network according to the connection strengths between

Geoffrey Hinton

neurons in adjacent layers, it'll eventually end up in that last layer, the one with the two neurons that say whether there's a hot dog in the picture. Since the picture is of a piano, ideally the "hot dog" neuron should have a zero on it, while the "not hot dog" neuron should have a high number. But let's say it doesn't work out that way. Let's say the network is wrong about this picture. Backprop is a procedure for rejiggering the strength of every connection in the network so as to fix the error for a given training example. The way it works is that you start with the last two neurons, and figure out just how wrong they were: how much of a difference is there between what the excitement numbers should have been and what they actually were? When that's done, you take a look at each of the connections leading into those neurons—the ones in the next lower layer—and figure out their contribution to the error. You keep doing this until you've gone all the way to the first set of connections, at the very bottom of the network. At that point you

A real intelligence doesn't break when you slightly change the problem.

know how much each individual connection contributed to the overall error, and in a final step, you change each of the weights in the direction that best reduces the error overall. The technique is called "backpropagation" because you are "propagating" errors back (or down) through the network, starting from the output.

The incredible thing is that when you do this with millions or billions of images, the network starts to get pretty good at saying whether an image has a hot dog in it. And what's even more remarkable is that the individual layers of these image-recognition nets start being able to "see" images in sort of the same way our own visual system does. That is, the first layer might end up detecting edges, in the sense that its neurons get excited when there are edges and don't get excited when there aren't; the layer above that one might be able to detect sets of edges, like corners; the layer above that one might start to see shapes; and the layer above that one might start finding stuff like "open bun" or "closed bun," in the sense of having neurons that respond to either case. The net organizes itself, in other words, into hierarchical layers without ever having been explicitly programmed that way.

This is the thing that has everybody enthralled. It's not just that neural nets are good at classifying pictures of hot dogs or whatever: they seem able to build representations of ideas. With text you can see this even more clearly. You can feed the text of Wikipedia, many billions of words long, into a simple neural net, training it to spit out, for each word, a big list of numbers that correspond to the excitement of each neuron in a layer. If you think of each of these numbers as a coordinate in a complex space, then essentially what you're doing is finding a point, known in this context as a vector, for each word somewhere in that space. Now, train your network in such a way that words appearing near one another on Wikipedia pages end up with similar coordinates, and voilà, something crazy happens: words that have similar meanings start showing up near one another in the space. That is, "insane" and "unhinged" will have coordinates close to each other, as will "three" and "seven," and so on. What's more, so-called vector arithmetic makes it possible to, say, subtract the vector for "France" from the vector for "Paris," add the vector for "Italy," and end up in the neighborhood of "Rome." It works without anyone telling the network explicitly that Rome is to Italy as Paris is to France.

"It's amazing," Hinton says. "It's shocking." Neural nets can be thought of as trying to take things—images, words, recordings of someone talking, medical data—and put them into what mathematicians call a high-dimensional vector space, where the closeness or distance of the things reflects some important feature of the actual world. Hinton believes this is what the brain itself does. "If you want to know what a thought is," he says, "I can express it for you in a string of words. I can say 'John thought, "Whoops."' But if you ask, 'What is the thought? What does it mean for John to have that thought?' It's not that inside his head there's an opening quote, and a 'Whoops,' and a closing quote, or even a cleaned-up version of that. Inside his head there's some big pattern of neural activity." Big patterns of neural activity, if you're a mathematician, can be captured in a vector space, with each neuron's activity corresponding to a number, and each number to a coordinate of a really big vector. In Hinton's view, that's what thought is: a dance of vectors.

It is no coincidence that Toronto's flagship AI institution was named for this fact. Hinton was the one who came up with the name Vector Institute.

There's a sort of reality distortion field that Hinton creates, an air of certainty and enthusiasm, that gives you the feeling there's nothing that vectors can't do. After all, look at what they've been able to produce already: cars that drive themselves, computers that detect cancer, machines that instantly translate spoken language. And look at this charming British scientist talking about gradient descent in high-dimensional spaces!

It's only when you leave the room that you remember: these "deep learning" systems are still pretty dumb, in spite of how smart they sometimes seem. A computer that sees a picture of a pile of doughnuts piled up on a table and captions it, automatically, as "a pile of doughnuts piled on a table" seems to understand the world; but when that same program sees a picture of a girl brushing her teeth and says "The boy is holding a baseball bat," you realize how thin that understanding really is, if ever it was there at all. Neural nets are just thoughtless fuzzy pattern recognizers, and as useful as fuzzy pattern recognizers can be—hence the rush to integrate them into just about every kind of software—they represent, at best, a limited brand of intelligence, one that is easily fooled. A deep neural net that recognizes images can be totally stymied when you change a single pixel, or add visual noise that's imperceptible to a human. Indeed, almost as often as we're finding new ways to apply deep learning, we're finding more of its limits. Self-driving cars can fail to navigate conditions they've never seen before. Machines have trouble parsing sentences that demand common-sense understanding of how the world works.

Deep learning in some ways mimics what goes on in the human brain, but only in a shallow way—which perhaps explains why its intelligence can sometimes seem so shallow. Indeed, backprop wasn't discovered by probing deep into the brain, decoding thought itself; it grew out of models of how animals learn by trial and error in old classical-conditioning experiments. And most of the big leaps that came about as it developed didn't involve some new insight about neuroscience; they were technical improvements, reached by years of mathematics and engineering. What we know about intelligence is nothing against the vastness of what we still don't know.

David Duvenaud, an assistant professor in the same department as Hinton at the University of Toronto, says deep learning has been somewhat like engineering before physics. "Someone writes a paper and says, 'I made this bridge and it stood up!' Another guy has a paper: 'I made this bridge and it fell down—but then I added pillars, and then it stayed up.' Then pillars are a hot new thing. Someone comes up with arches, and it's like, 'Arches are great!'" With physics, he says, "you can actually understand what's going to work and why." Only recently, he says, have we begun to move into that phase of actual understanding with artificial intelligence.

Hinton himself says, "Most conferences consist of making minor variations … as opposed to thinking hard and saying, 'What is it about what we're doing now that's really deficient? What does it have difficulty with? Let's focus on that.'"

It can be hard to appreciate this from the outside, when all you see is one great advance touted after another. But the latest sweep of progress in AI has been less science than engineering, even tinkering. And though we've started to get a better handle on what kinds of changes will improve deep-learning systems, we're still largely in the dark about how those systems work, or whether they could ever add up to something as powerful as the human mind.

It's worth asking whether we've wrung nearly all we can out of backprop. If so, that might mean a plateau for progress in artificial intelligence.

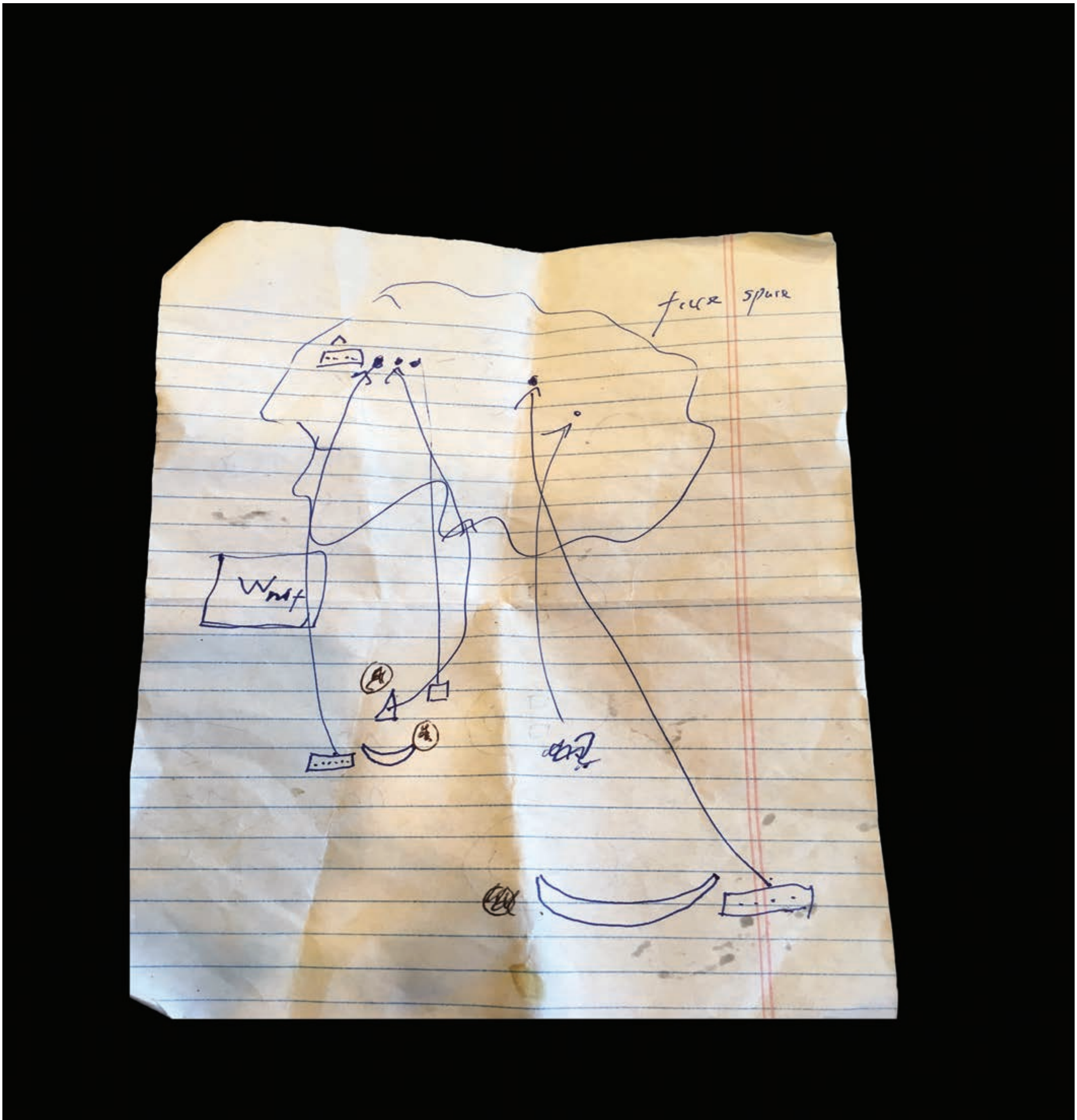
Patience

If you want to see the next big thing, something that could form the basis of machines with a much more flexible intelligence, you should probably check out research that resembles what you would've found had you encountered backprop in the '80s: smart people plugging away on ideas that don't really work yet.

A few months ago I went to the Center for Minds, Brains, and Machines, a multi-institutional effort headquartered at MIT, to watch a friend of mine, Eyal Dechter, defend his dissertation in cognitive science. Just before the talk started, his wife Amy, their dog Ruby, and their daughter Susannah were milling around, wishing him well. On the screen was a picture of Ruby, and next to it one of Susannah as a baby. When Dad asked Susannah to point herself out, she happily slapped a long retractable pointer against her own baby picture. On the way out of the room, she wheeled a toy stroller behind her mom and yelled "Good luck, Daddy!" over her shoulder. "Vámanos!" she said finally. She's two.

Eyal started his talk with a beguiling question: How is it that Susannah, after two years of experience, can learn to talk, to play, to follow stories? What is it about the human brain that makes it learn so well? Will a computer ever be able to learn so quickly and so fluidly?

We make sense of new phenomena in terms of things we already understand. We break a domain down into pieces and learn the pieces. Eyal is a mathematician and computer programmer, and he thinks about tasks—like making a soufflé—as really complex computer programs. But it's not as if you learn to make a soufflé by learning every one of the program's zillion micro-instructions, like "Rotate your elbow 30 degrees, then look down at the countertop, then extend your pointer finger,



Hinton made this sketch for his next big idea, to organize neural nets with "capsules."

then …" If you had to do that for every new task, learning would be too hard, and you'd be stuck with what you already know. Instead, we cast the program in terms of high-level steps, like "Whip the egg whites," which are themselves composed of subprograms, like "Crack the eggs" and "Separate out the yolks."

Computers don't do this, and that is a big part of the reason they're dumb. To get a deep-learning system to recognize a hot dog, you might have to feed it 40 million pictures of hot dogs. To get Susannah to recognize a hot dog, you show her a hot dog. And before long she'll have an understanding of language that goes deeper than recognizing that certain words often appear together. Unlike a computer, she'll have a model in her mind about how the whole world works. "It's sort of incredible to me that people are scared of computers taking jobs," Eyal says. "It's not that computers can't replace lawyers because lawyers do really complicated things. It's because lawyers read and talk to people. It's not like we're close. We're so far."

A real intelligence doesn't break when you slightly change the requirements of the problem it's trying to solve. And the key part of Eyal's thesis was his demonstration, in principle, of how you might get a computer to work that way: to fluidly apply what it already knows to new tasks, to quickly bootstrap its way from knowing almost nothing about a new domain to being an expert.

Essentially, it is a procedure he calls the "exploration–compression" algorithm. It gets a computer to function somewhat like a programmer who builds up a library of reusable, modular components on the way to building more and more complex programs. Without being told anything about a new domain, the computer tries to structure knowledge about it just by playing around, consolidating what it's found, and playing around some more, the way a human child does.

His advisor, Joshua Tenenbaum, is one of the most highly cited researchers in AI. Tenenbaum's name came up in half the conversations I had with other scientists. Some of the key people at DeepMind—the team behind AlphaGo, which shocked computer scientists by beating a world champion player in the complex game of Go in 2016—had worked as his postdocs. He's involved with a startup that's trying to give self-driving cars some intuition about basic physics and other drivers' intentions, so they can better anticipate what would happen in a situation they've never seen before, like when a truck jackknifes in front of them or when someone tries to merge very aggressively.

Eyal's thesis doesn't yet translate into those kinds of practical applications, let alone any programs that would make headlines for besting a human. The problems Eyal's working on "are just really, really hard," Tenenbaum said. "It's gonna take many, many generations."

Tenenbaum has long, curly, whitening hair, and when we sat down for coffee he had on a button-down shirt with black slacks. He told me he looks to the story of backprop for inspiration. For decades, backprop was cool math that didn't really accomplish anything. As computers got faster and the engineering got more sophisticated, suddenly it did. He hopes the same thing might happen with his own work and that of his students, "but it might take another couple decades."

As for Hinton, he is convinced that overcoming AI's limitations involves building "a bridge between computer science and biology." Backprop was, in this view, a triumph of biologically inspired computation; the idea initially came not from engineering but from psychology. So now Hinton is trying to pull off a similar trick.

"The fact that it doesn't work is just a temporary annoyance."

Neural networks today are made of big flat layers, but in the human neocortex real neurons are arranged not just horizontally into layers but vertically into columns. Hinton thinks he knows what the columns are for—in vision, for instance, they're crucial for our ability to recognize objects even as our viewpoint changes. So he's building an artificial version—he calls them "capsules"—to test the theory. So far, it hasn't panned out; the capsules haven't dramatically improved his nets' performance. But this was the same situation he'd been in with backprop for nearly 30 years.

"This thing just has to be right," he says about the capsule theory, laughing at his own boldness. "And the fact that it doesn't work is just a temporary annoyance."

James Somers is a writer and programmer based in New York City. His previous article for MIT Technology Review *was "Toolkits for the Mind" in May/June 2015, which showed how Internet startups are shaped by the programming languages they use.*

Fearsome Machines: A Prehistory

Ever since the beginning of industrial society, people have simultaneously marveled at the power of automation and lamented that human capabilities are being irredeemably devalued.

1811 – Demanding better conditions and higher pay, textile workers in England smash machinery and set factories on fire. These workers will come to be known as Luddites, after their mythical leader, Ned Ludd, and the name will become a synonym for opponents or critics of technology. But it's a misnomer: this is a class protest more than a technological one. The stocking-frame machines the Luddites vandalize have been around since the 1600s.

1829 – Grappling with the meaning of the "mechanical age," the philosopher Thomas Carlyle notes that industry has made society richer, and that people are generally better "fed, clothed, lodged, and, in all outward respects, accommodated." But he questions an increasing "distance between the rich and the poor" and notes a "mighty change" in "modes of thought and feeling": "Men are grown mechanical in head and in heart, as well as in hand." Will civic life lose its soul? After all, "government includes much also that is not mechanical, and cannot be treated mechanically."

1842 – Ada Lovelace envisions how a calculating machine "might act upon other things besides number[s]"—for example, composing music. She also shows how the machine could be made to determine "that which human brains find it difficult or impossible to work out unerringly."

1868 – "Calculation and reasoning, like weaving and plowing, are work, not for human souls, but for clever combinations of iron and wood. If you spend time in doing work that a machine could do faster than yourselves, it should only be for exercise."
— *Mary Everest Boole*

1917 – "The machine is the very image of efficiency—governed, deadly, predestinarian. But it is an efficiency against which nature cries out; it is an efficiency destitute of that adaptability of means and idealization of ends which is the human essence of true reason." —*Hartley Burr Alexander*

1955 – Mathematics professor John McCarthy calls for researchers to join him the following summer at Dartmouth College to build the foundation for artificial intelligence. He says, "Every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it."

1977 – McCarthy predicts that bringing AI to the level of humans will take "five to 500 years."

2009 – "The economic problems of the future will not be about growth but about something more nettlesome: the ineluctable increase in the number of people with no marketable skills, and technology's role not as the antidote to social conflict, but as its instigator." —*Gregory Clark*

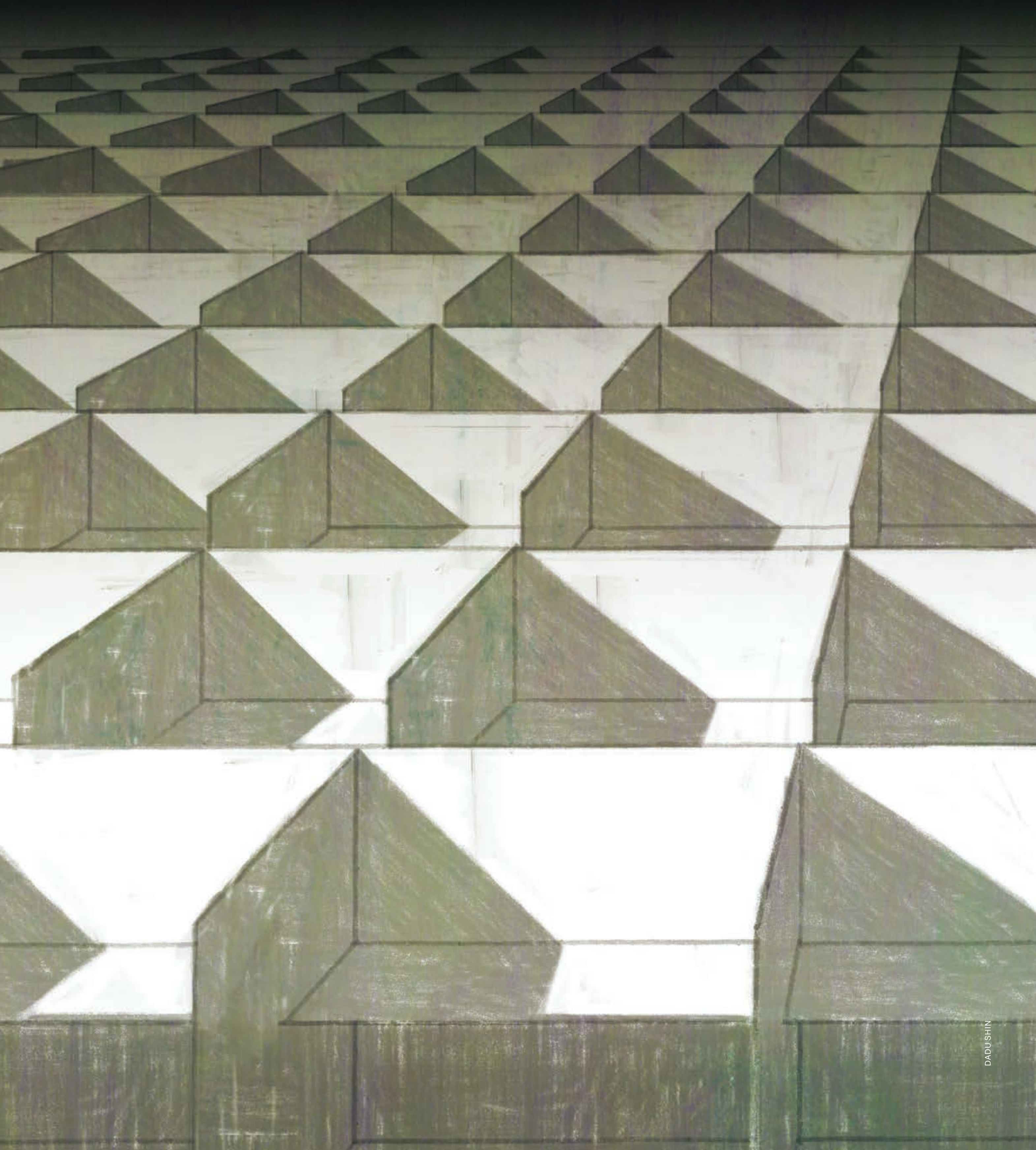
2014 – "I think we should be very careful about artificial intelligence. If I were to guess what our biggest existential threat is, it's probably that. With artificial intelligence we are summoning the demon."
—*Elon Musk*

2016 – After studying the economic effects of advances in AI, the Obama White House suggests increases in the minimum wage, new training programs, and policies aimed at helping workers adjust. But it says the more aggressive step of enacting a universal basic income could be "counterproductive": "We should not advance a policy that is premised on giving up on the possibility of workers' remaining employed."

2017 – Russian president Vladimir Putin says that whichever country leads the development of AI will be "the ruler of the world."

MIGUEL PORLAN

India Warily Eyes AI



DADU SHIN

Technology outsourcing has been India's only reliable job creator in the past 30 years. Now artificial intelligence threatens to wipe out those gains.

By Samanth Subramanian

Two days after K.S. Sunil Kumar received a promotion, Human Resources phoned him up and asked him to resign.

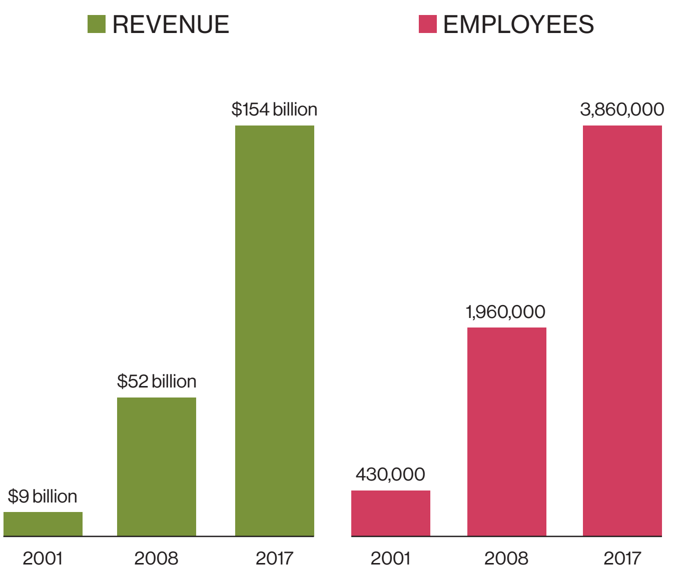
This happened in April, just as Kumar was beginning his ninth year at Tech Mahindra, one of the giants in India's IT services industry. He worked in engineering services, where he designed components and tools for aerospace firms in North America and Europe. They'd send over specs—the materials available to construct a hinge, and the kind of load it had to bear, and the cost at which it had to be manufactured—and he mocked up options with the help of software. He was a foot soldier in the army of Indian engineers to whom work is outsourced from the West, so that it can be finished at a fraction of the expense. Sometimes he left his base, Tech Mahindra's Bangalore campus, to serve stints at clients' offices abroad: in Montreal, Belfast, or Stockholm. When his employment was terminated, Kumar was earning close to $17,000 annually, a nice middle-class salary in India. Around the same time, Tech Mahindra announced profits for the previous financial year of $419 million, on revenue of $4.35 billion. (Tech Mahindra did not respond to a request for comment for this story.) IT services and related offerings in India record annual revenue of $154 billion and employ nearly four million people. The sector's vigor has relied upon its ability to shave costs lower and lower—upon its ability to arbitrage the cheaply bought skills of workers like Sunil Kumar.

Bangalore is filled with IT professionals and engineers who resemble him. His curly hair is thin on top and gray at the temples; when we spoke he was wearing a faded checked Tommy Hilfiger shirt, a backpack, and a look of subdued anxiety. He grew up in a village a few hundred miles from Bangalore, where his father wove silk saris on a handloom. In 1995, when he was 15, he moved to Bangalore to study for a diploma in mechanical engineering; it was a step below a university degree, which he would gain later through a correspondence course. Until he joined Tech Mahindra, in the summer of 2008, Kumar worked as a draftsman at an aerospace firm. The new job opened his life up the way the IT industry did for so many Indians, offering a chance to vault from a blue-collar background to a white-collar future. He got married, and the couple had a son; he took out a loan of $47,000 to buy a house, so that his parents and two brothers, who followed him to Bangalore, could stay with him. "I live a middle-class life," he says. "I don't want to showcase to people that I'm doing an IT job. Branded shirts, shoes—I don't want them."

When Kumar lost his job, he became part of a wave of layoffs washing through the Indian IT industry—a term that includes, in its vastness, call centers, engineering services, business process outsourcing firms, and infrastructure management and software companies. The recent layoffs are part of the industry's most significant period of churn since it began to boom two decades ago. Companies don't necessarily attribute these layoffs directly to automation, but at the same time, they constantly identify automation as the spark for huge changes in the industry. Bots, machine learning, and algorithms that robotically execute processes are rendering old skills redundant, recasting the idea of work and making a smaller labor force seem likely. An analysis by the business newspaper *Mint* reported that the top seven IT firms in India will lay off at least 56,000 employees this year. After its annual general meeting this summer, the $10 billion behemoth Infosys announced that 11,000 of its 200,000 employees had been "released" from repetitive tasks by automation and redeployed elsewhere within the company, the burden of their previous work now borne by algorithms. HfS Research, which studies the IT industry, predicted last year that automation will result in a net loss of 480,000 jobs in India by 2021. "If we sit still, there is absolutely no doubt that our jobs are going to be wiped out by AI," Vishal Sikka said in March, when he was still the CEO of Infosys. (Sikka resigned in August.) "Sixty to 70 percent over the next 10 years—or maybe less than 10 years—of the jobs that we do today are going to be replaced by AI … unless we continue to evolve ourselves."

Ultra-Fast Growth

The IT and business process outsourcing industry has become the largest private-sector employer in India.



The fear that AI is pulverizing jobs is not unique to India, but automation could hit this country particularly hard because so much of its high-tech economy involves relatively routine work that is prime for computers to take over. In some cases, Indian IT services companies will automate the work themselves. In other cases, companies in the West will do it, so they no longer have to farm work out to humans in India.

Sunil Kumar wasn't told, in any detail, why he was being let go; he insists that what he did at Tech Mahindra wasn't automatable, and that he was fired as part of a drive to invigorate the bottom line. Devika Narayan, a sociologist at the University of Minnesota who is researching the subject for her doctoral thesis, thinks automation may indeed be getting too much blame for the loss of jobs like his. Companies might well be talking up automation to mask some of their own failures, or to distract from the ill effects of other factors beyond their control, she says. She points out that many IT giants are flabby and overstaffed, and that American companies are now wary, given the U.S. political climate, of sending work overseas. "The extent to which automation is being exaggerated is still unclear to me," Narayan says. She suspects that Indian IT companies "want to leverage this automation narrative to undertake structural changes, particularly downsizing.'"

Where the truth lies is important for India. The IT industry may employ only a few million of India's 1.3 billion people—but it has been a beacon for young men and women with aspirations. It motivated families to send their children to university, placed graduates in gleaming campuses, conferred independent urban lifestyles upon them, and provided stable incomes and access to the world outside India. Over the last 30 years, moreover, it has been the only industry in India to begin from seed and bloom to such success. India is otherwise struggling to create jobs: 12 million Indians enter the workforce every year, but only 135,000 jobs in the formal economy's eight biggest sectors—including IT—were created in 2015. A dramatic contraction of the IT industry—a dimming of the beacon—would jolt the country's economy and polity deeply.

Taking out the swivel chairs

Chetan Dube says he saw it coming. In 2005, Dube, the CEO of a company called IPsoft, was addressing a forum of IT companies in Mumbai. "If Indian industry does not wake up to the automation wave that is coming, then we will face an existential crisis," he remembers telling the gathering. "I got chastised. The next day, we were having breakfast, and at the back of the *Economic Times*, an article said: 'IPsoft CEO predicts the death of Indian outsourcing.'"

Dube, a bow-tied and suspendered mathematician who once taught at New York University, founded IPsoft in 1998, but it was in 2014 that the company launched what is now its flagship product, Amelia. A conversational service agent, Amelia is designed to replace the humans who field customer queries in call centers and back offices. Amelia has been used to resolve suppliers' questions for a large oil and gas firm; it runs the live chat service for SEB, a Swedish bank; it works in another bank's team of mortgage brokers. For one client, Dube says, the average time to reach a conventional offshore agent used to be 55 seconds; an incarnation of Amelia made itself available in two seconds or less. An offshore agent needed 18.2 minutes, on average, to resolve a query successfully; for Amelia, it was 4.5 minutes. The customer service sphere is filling rapidly with products like Amelia—chatbots that, through text or voice, obviate the human presence altogether.

Automation could hit India particularly hard because much of its high-tech economy involves relatively routine work that is prime for computers to take over.

Only in a few cases has Amelia directly supplanted Indian workers, but Dube thinks that further change is inevitable. Call centers in India are already in flux: salaries have crept up, attrition has always been high, and firms like Infosys and Tata Consultancy Services have offshored some of their functions farther out to Manila, where labor costs are even lower than in India. (Three years ago, one official in an industry body named Assocham predicted gloomily that India would lose $30 billion in call center revenues to the Philippines over the following decade.) In the West, some companies are repatriating their

DATA FROM NATIONAL ASSOCIATION OF SOFTWARE AND SERVICES COMPANIES voice service operations, while others are abandoning them altogether in favor of e-mail or chat help desks.

The prospect—or fear—of automation has thus become one more force reshaping the call center business. Voice recognition isn't anywhere close to perfect yet, and even the sophisticated cognitive agents of the vaunted near future may not be able to parse rambling customers, complicated problems, or uncommonly thick accents. But most voice work is prosaic and repetitive. Given that humans in the first tier of this service calibrate their responses with the help of a script, their functions are among the simplest to transform into machine code.

Other fruit hangs similarly low elsewhere in the sector; as Dube says, "India is nothing but the blue-collar worker of IT," so the lowest layer of work is plump with tasks that need diligence and stamina but not creativity or sharp technical skill.

At Genpact, a 20-year-old company in the industry of business process outsourcing, there's a lot of "swivel-chair work," says Gianni Giacomelli, who leads the firm's digital solutions business. The term captures the mechanical nature of these tasks. Until recently, a human has been required to deal with software systems that help with enterprise functions. Those systems are often disconnected from each other, so Genpact's employees "are asked to process, very basically, things that come from one system and go into another system," he says. "That toggling back and forth is a massive waste of time." Since 2014, Genpact has been replacing workers in swivel chairs by ordering computers to take information from screens and servers and convey it into another system.

One level up is the kind of work that Giacomelli calls "reconciliation": examining invoices and bills from a client's various vendors and customers, with all their discrepancies and contradictions. It isn't trivial work; it involves, right now, some grains of human judgment. "But once machines have seen enough of those things, they can do that kind of stuff," he says.

Mayhem

For some of its clients, the IT colossus Infosys has been able to automate nearly all of the most routine chores of monitoring and maintaining their data infrastructure, says S. Ravi Kumar, the company's deputy COO. Some intermediate work, such as triaging IT service requests, is now done by machines as well. At a still-higher level of service complexity—jobs that involve troubleshooting bugs deep within the code, or developing solutions to new problems—35 to 40 percent of tasks are performed by automated routines.

Overall, Somak Roy, an analyst at Forrester Research, estimates that only a quarter of the most easily automated work in India is being completed exclusively by machines. Companies are still enthusiastically dabbling in technologies that remain nascent. Nonetheless, Roy calls it a "distinct possibility" that IT will "cease to be a large-scale employment generator in India."

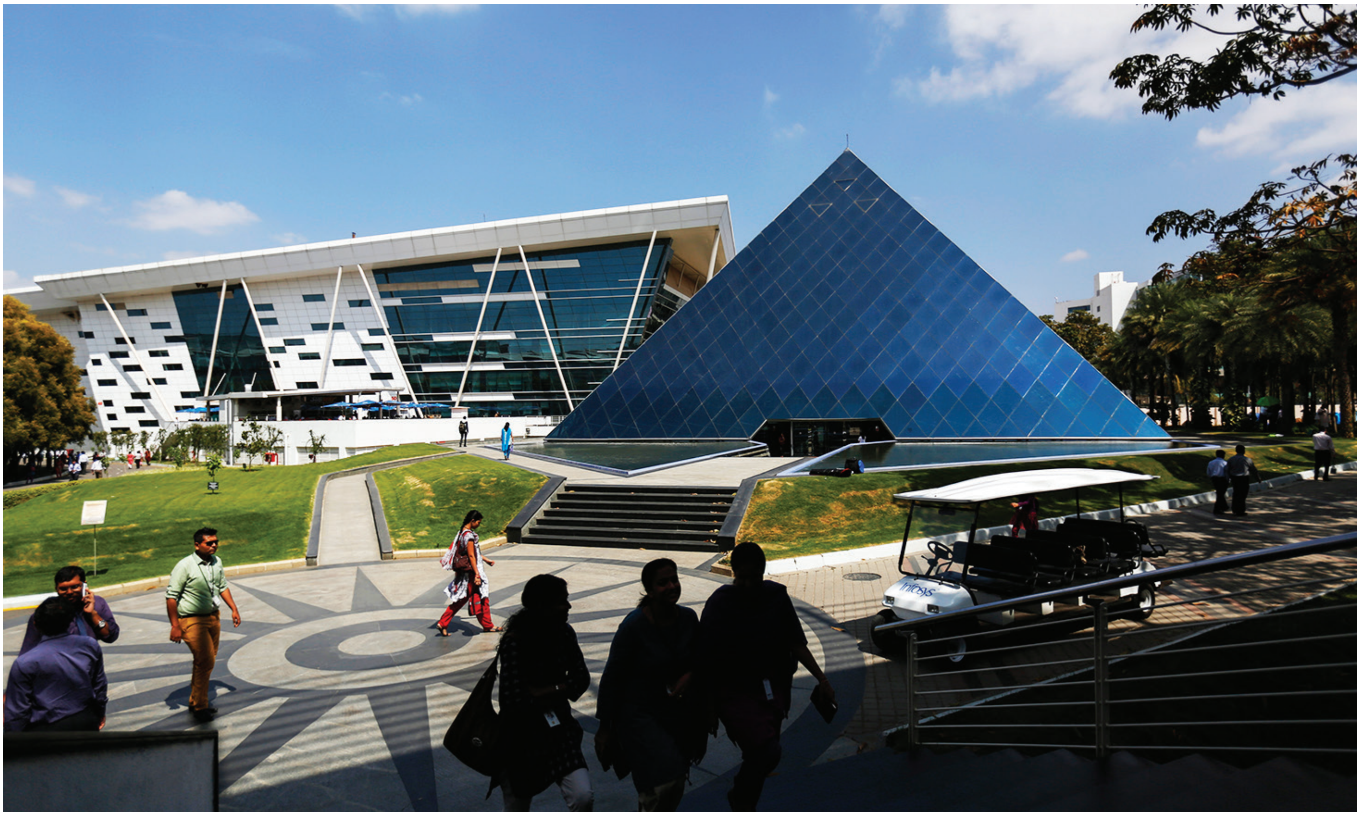
One of the direst visions comes from Pankaj Bansal, the chief executive of PeopleStrong, a human-resources firm that frequently staffs IT companies with engineers. For IT services firms in the shape and form India has known them, Bansal says, "it will be mayhem." He has been accused of fearmongering, but he holds fast to his assessment. Over the last two years, three or four out of every 10 jobs in the bottom layer of the pyramid of

Bansal reckons that the IT sector hired 400,000 people annually until two or three years ago, and that the number has now shrunk to 140,000 to 160,000. Soon, he says, "net hiring will be barely above zero."

IT work have been "squashed" by automation, he says—and this has been manifested not in how many people have been laid off but in how sharply recruitment has dropped. Companies once gusted through the campuses of engineering colleges, picking them clean of fresh graduates. Bansal reckons that the IT sector hired 400,000 people annually until two or three years ago, and that the number has now shrunk to 140,000 to 160,000. Soon, he says, "net hiring will be barely above zero."

Bansal's prophesy of a deflating workforce may well come true for another reason. For years, IT firms hired inexpensive,

INDIAPICTURES/UIG VIA GETTY IMAGES



The size and prestige of India's IT industry are reflected in the design of Infosys campuses in Mysore (top) and Bangalore.

hardworking youngsters wholesale—even if they were poorly skilled—because it made sense to staff projects heavily. The more warm bodies assigned to a task, the higher the bill that could be presented to the client. But the practice of calculating bills in this manner has waned; customers now pay for outcomes and impact. Meanwhile, the poorly skilled youngsters who stayed with their firms have received promotions and raises with clockwork regularity, until they've turned into mid-rung engineers who are now too costly, in their thousands, to sustain. Cue the purges.

Within the industry, Bansal's grim views encounter profound disagreement, at least in public. Perhaps this is understandable: it has never been wise for companies to be effusive about the imminence of layoffs and workforce reductions. Sangeeta Gupta, a senior vice president at an industry body called the National Association of Software and Services Companies, predicts only a "decoupling" of revenues and head count over the next few years. If Indian IT required three million employees to touch $100 billion in annual revenue, she says, it will need only 1.2 million to two million additional people for its next $100 billion. By 2025, when revenues reach $350 billion, Gupta predicts, the sector will have added another 2.5 million to three million jobs to the four million it holds today.

There is a tension between the long arc of technological revolutions and the far shorter one of human lives.

Companies are eager to explain why automation won't hollow out, and might even expand, their swarms of employees. For one thing, it isn't as if machines can make people instantly redundant. "Jobs are not structured in such a clean way," says Giacomelli, at Genpact. The architectures of modern work that have developed over decades all have human beings at their center; they rely upon people's agility and their capacity to hold different things in their minds. "People do many things, so it's not that easy to extricate one task or the other and make that happen through AI," he says.

Companies also insist that they want to reskill the employees who risk being supplanted by automation. If an engineer's work is best taken over by an algorithm, "it isn't fair to then say 'You don't have a job,'" says K.M. Madhusudhan, the CTO of Mindtree, a services firm that employs more than 16,000 people. "Can we teach this engineer programming? Maybe not heavy lifting, but some scripting, which is not that difficult. For every role, we believe, there are adjacent, higher-level skills that can be acquired." Madhusudhan calls this a "humane approach." It will result in fewer job losses, although he acknowledges that firms like his will also be creating fewer jobs. "The numbers that were possible before will not be possible in the future," he says. "That is the bigger concern for a country like India, because we still produce a lot of engineers, and not everyone will get a job."

This is a familiar pattern in history: every technological stride forward has meant that the same amount of work can be done by fewer people. "Whenever there's a revolution, there's a worry about fewer jobs. It happened with the Industrial Revolution as well," says Ravi Kumar, at Infosys. "The reality is, though, that there's more consumption," he adds. That eventually increases the need for new kinds of labor. At the moment, he says, enterprises spend 65 to 70 percent of their IT budgets "just to keep the lights on"—to pay for infrastructure and routine support. If that money is undammed, it may well pour into new—and as yet unimagined—streams of revenue and employment: "It would mean a much bigger canvas for us."

But even if he is right, there is a tension between the long arc of these revolutions and the far shorter one of human lives. In the near term, people will lose their livelihoods. Sunil Kumar is still without a job.

In June, he filed a petition for wrongful dismissal with the office of the labor commissioner, a state body that resolves industrial disputes and enforces labor laws. Once, when he checked on its progress, an official advised him that his fight was likely to be a lengthy one, and now he suspects nothing will come of it. "Whatever confidence I had, I'm losing it," he says. When he reads his newspapers, he stops just short of the business pages, which frustrate him. "There will be companies saying many things: 'We're hiring this many people, there are many opportunities.' The CEOs keep saying it. I stopped reading all this," he says. He knows he ought to start looking for a new job, but he hasn't been able to pull himself together; it is as if his dismissal had stymied life itself. "I haven't been able to concentrate on anything," he says. "It's very difficult now."

Samanth Subramanian has written for such publications as Wired, *the* New York Times Magazine, *and the* New Yorker. *His most recent book is* This Divided Island: Life, Death, and the Sri Lankan War.

The Dangers of Tech-Bro AI

Tabitha Goldstaub, a cofounder of CognitionX, which helps companies deploy AI, says that diversifying the field is necessary to make sure products actually work well.

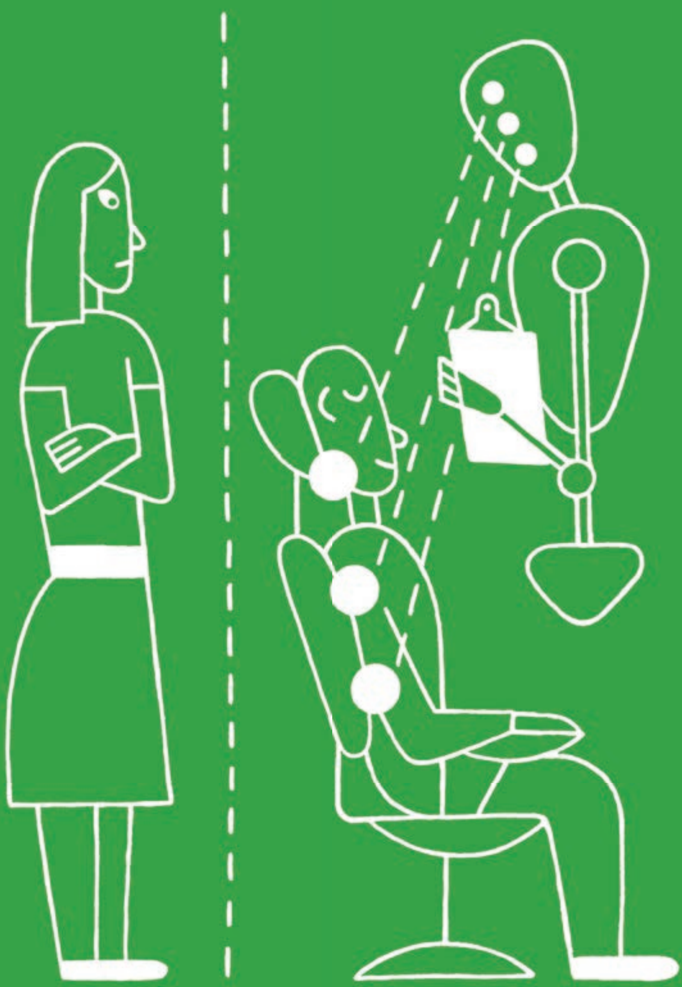
If you think about artificial intelligence and the core components of what makes an AI, you have the fact that it's given a goal and then will find a way to reach that goal. It's then often very un-transparent as to how it reached that goal. If you're building into a machine some unconscious bias, you might not know that it's there; the output could be detrimental to women and it's very tough to work out exactly why that has happened.

In traditional technology, you can see [what has happened]: women dying in car crashes because the crash-test dummies were the shape of a man rather than the shape of a woman. [With AI there could be] similar life-or-death situations, in drug trials or in autonomous vehicles and things like that.

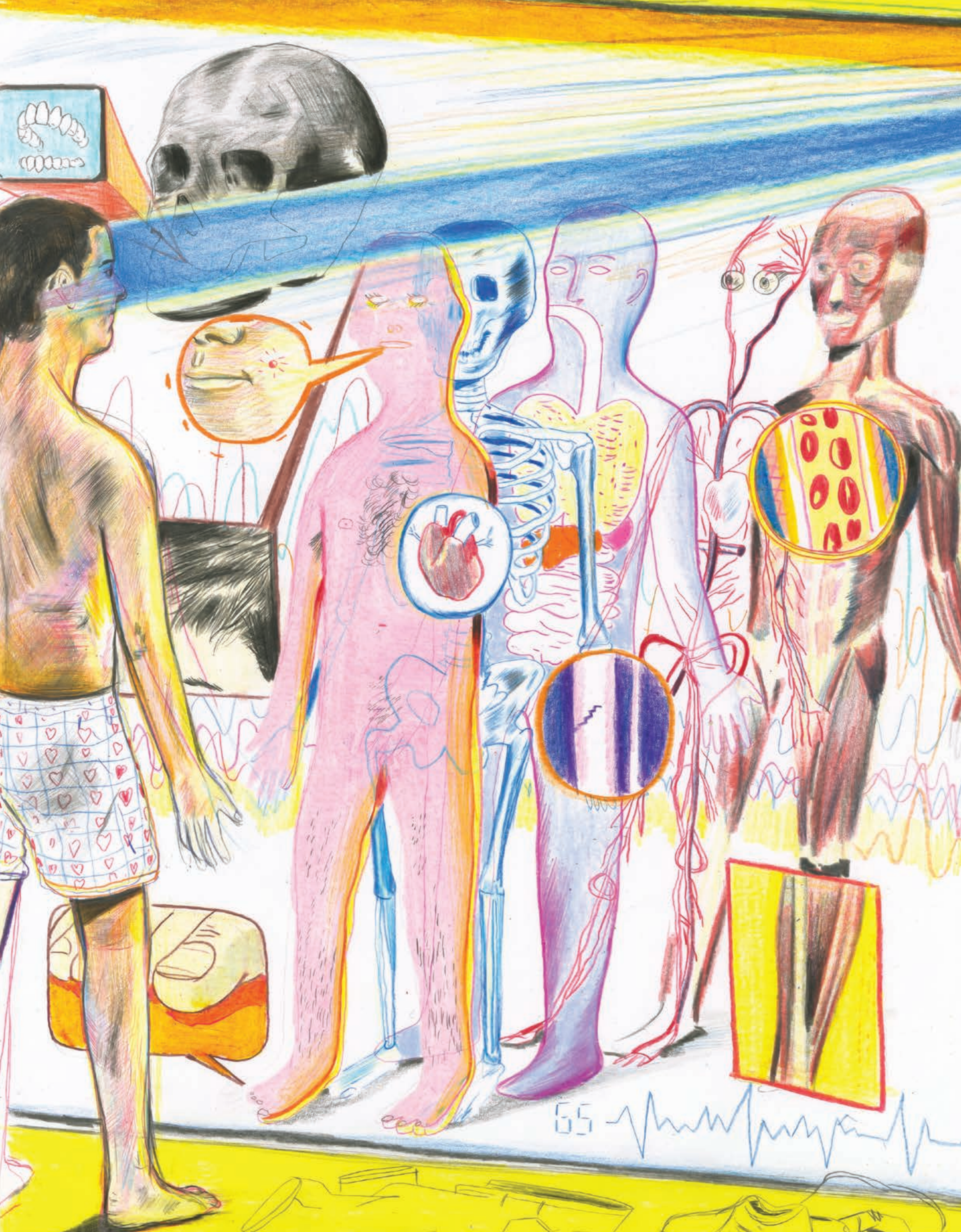
There are some examples of [gender bias in AI today]: Google ads displaying higher-earning [job] ads to men than women. We can hypothesize other types of situations that would happen—what if women weren't as able to get loans or mortgages or insurance?

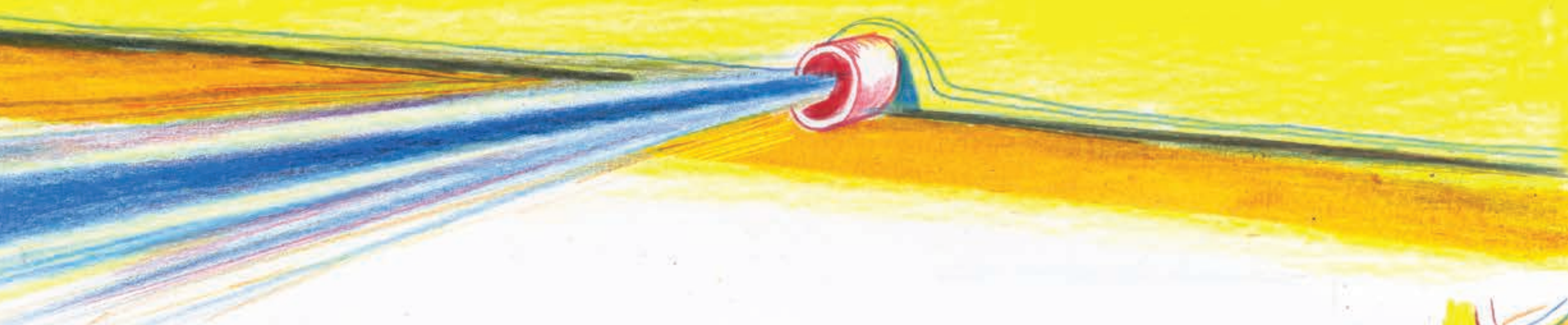
I don't have a dystopian view of AI. I don't see killer robots. I'm so much more focused on the narrow applications, and I think that if you look at every single one of those narrow applications there is a chance that it negatively affects women. I don't think artificial intelligence is the issue here; it's the additional issue rather than the cause. We're talking about the risk that our unconscious sexism or unconscious racism seep into the machines that we're building.

How do we get anyone who's building AI to think about these things? We need to have consumers demand ethical AI. Not enough people are seeing this as more than just a gender issue; this is an actual, fundamental product issue. *—as told to Rachel Metz*



MIGUEL PORLAN


65



By David Ewing Duncan
Illustrations by Yann Kebbi

Constant Monitoring + AI = Rx for Personal Health

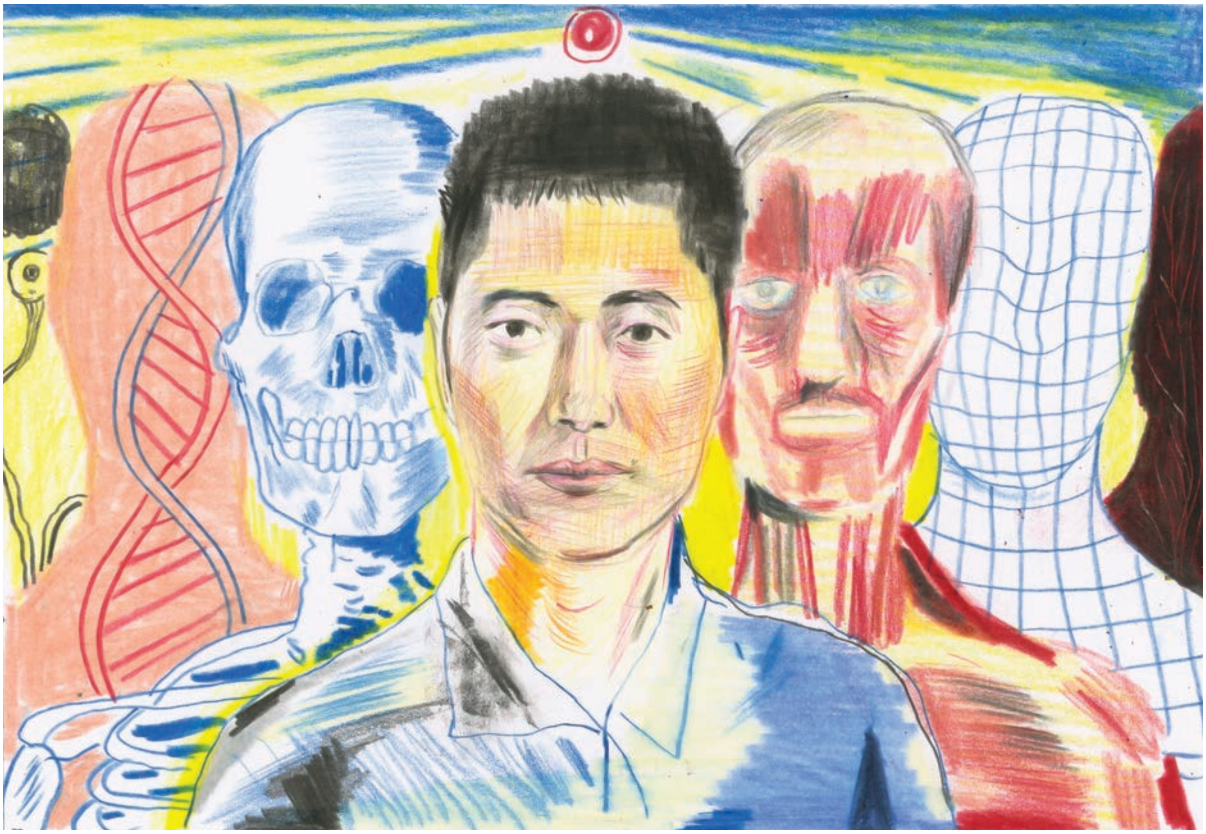
An audacious Chinese entrepreneur wants to test your body for everything. But are computers really smart enough to make sense of all that data?

"This smart mirror isn't very smart," says Jun Wang, standing in front of a full-length mirror wearing designer jeans ripped at the knees. "It's just a camera and a mirror," he says, looking mildly distressed—or as distressed as possible for a man whose face is perpetually unperturbed. "What I want is a mirror that does a 3-D scan of me here," he says, using his hands to trace the contour of his thighs, "and here." Wang indicates his belly, which is lean. "We want an exact 3-D figure of you: the fat, the muscle—your entire body shape, plus facial recognition, and what's going on with your skin." He points to the top right area of the mirror. "And I want readouts about my health up there, next to where I'm brushing my teeth—my weight, blood pressure, and heart rate, and how does that correlate with my DNA?"

This as-yet-unrealized smart mirror is just one of several gadgets that Wang, a 41-year-old biologist and computer scientist turned entrepreneur, says he is building. The devices will help gather, analyze, and display a crush of health data he wants to collect about himself—and, he hopes, from millions of others. This is why Wang cofounded iCarbonX (ICX), a highly ambitious, if quixotic, personal-health company based here in Shenzhen, in southern China.

ICX wants to capture more data about your body than has ever before been possible. It starts with your DNA sequence and includes data from Fitbit-style wearables that measure your steps, heart rate, and sleep patterns. Add frequent blood tests to measure various proteins and enzymes that can, say, reflect the health of your heart or signal very early signs of cancer. Include monitoring of the ever-changing levels of metabolites produced by the body as it processes food; traditional blood tests on levels of cholesterol and glucose; heart data from an EKG; and information from your medical history. The goal: continuous monitoring of your health and suggestions of adjustments you might make in your diet and behavior before you slip from being healthy into the early stages of an illness.

This sounds a little like personalized medicine, which has been discussed for years. But for Wang, it's not just about treating disease. It's also about what might be termed personalized health. "Right now you don't know about your temperature, or your pulse, or the microbes inside you that affect your emotions," he says. "Or what to do if you have an allergy, or you want to lose weight because you're fat."



This vision of personal health monitoring is becoming achievable in part because of dramatic cost reductions for sequencing DNA and measuring the many thousands of biological compounds and processes that regulate the body. What all that means for any one of us, especially when all the readings are combined, is unclear. But ICX is part of a new wave of companies that figure they can find something meaningful in the data and enable medicine to stop merely reacting to an illness you have; these companies want to keep you healthy at a fraction of the cost. Unlocking this puzzle, with its millions of moving pieces, is where AI and other advanced computing techniques will have to come in. "AI is how we can take all of this information and tell you things that you don't know about your health," says Wang.

Assuming it works, putting all of this together will not be cheap. As CEO of ICX, Wang has raised $600 million in funding for the effort, a remarkable amount for a project offering high-tech tests for healthy people. "But he'll need it, and probably more, with everything they want to test," says Eric Schadt, a computational biologist and mathematician who recently stepped down as director of Mount Sinai's Icahn Institute for Genomics and Multiscale Biology in New York. Schadt has launched his own health data company, called Sema4, which is scanning genomes and molecular biomarkers.

ICX is using its pile of cash in part to invest in or acquire companies that might contribute to Wang's holistic vision. This includes a $161 million stake in Colorado-based SomaLogic, which is working on a chip that can measure 5,000 proteins in the blood; more than $100 million in PatientsLikeMe, a company in Cambridge, Massachusetts, that provides an online platform for more than 500,000 patients to share experiences, metrics, and feelings about their health and diseases; and $30 million in AOBiome, also of Cambridge, which sells spray-on microbes that it says make skin healthier. ICX also recently invested in HealthTell of San Ramon, California, which identifies antibodies from a blood sample as clues to the presence and progress of diseases including cancer and autoimmune disorders. Additionally, ICX is collaborating with several companies in China.

Tying this eclectic alliance together is an aggressive effort to build an artificial-intelligence system that will attempt to analyze this tremendous amount of data. That's being led by iCarbonX-Israel, which ICX acquired last year. Founded in 2005 as Imagu Vision Technologies, the company develops software to interpret CT scans and other medical images. Now Imagu's engineers are working with counterparts at ICX to create what they call a "virtual health brain" that will interpret the thousands of data points ICX wants to collect on each customer. "We want to create a tool that not only analyzes data but offers ways to help people improve their health, like how to alter their diet," says Imagu CEO and cofounder Mor Amitai.

"If this all sounds ridiculously complicated, it is," says Wang, smiling in a way that blends reassurance—which undoubtedly is appreciated by investors—and bemusement, as if he knows that what he is proposing sounds a bit daft. The question, then: can he use his money and technical savvy to revolutionize medicine?

> The devices will help gather, analyze, and display a crush of health data he wants to collect about himself – and, he hopes, from millions of others.

Precision health

A tall man with short black hair, Wang strolls coolly through his company's headquarters, a Silicon Valley knockoff with open workstations, glass-walled conference rooms, a gym, and a café always stocked with food, healthy drinks, tea, and coffee. It's on the third floor of an industrial-park building in a complex of similarly unexceptional structures tucked between two sprawling, wooded theme parks called Happy Valley and the China Folk Culture Village. In the back of ICX's HQ is Wang's office, a comfortable niche with deep leather chairs and a private conference room—a business setting that is a long way from where Wang started, as an academic researcher sequencing DNA at Beijing University in the late 1990s.

Wang authored over 100 studies as a professor at the University of Copenhagen and as a bioinformatics whiz at the Beijing Genomics Institute (BGI), which he helped found in 1999.

BGI was the organization that led China's relatively small contribution to the Human Genome Project, a worldwide effort in which several countries worked on different segments of the human DNA sequence published in 2003. BGI later churned out the first complete DNA sequences of an Asian person, a strain of rice, the SARS virus, and the giant panda. During his stint as BGI's CEO, Wang helped build the company into one of the largest sequencing operations in the world. In 2016, it had revenue of $250 million, and this summer it issued an IPO. Wang remains a major BGI shareholder and a member of the board.

But he left the company in 2015 because he was frustrated by the limits of genomics. Specifically, sequencing DNA doesn't provide much insight into the health of most individuals. Scientists have found countless DNA markers that seem as if they should help determine whether a person is healthy or sick. But those markers have turned out, nearly 15 years after the completion of the Human Genome Project, to make less of a difference than originally thought. With the exception of certain rare genetic mutations, DNA is just one determinant of a person's medical fate. "It turns out you also need to know about proteins, and metabolites, and all the rest," says Wang.

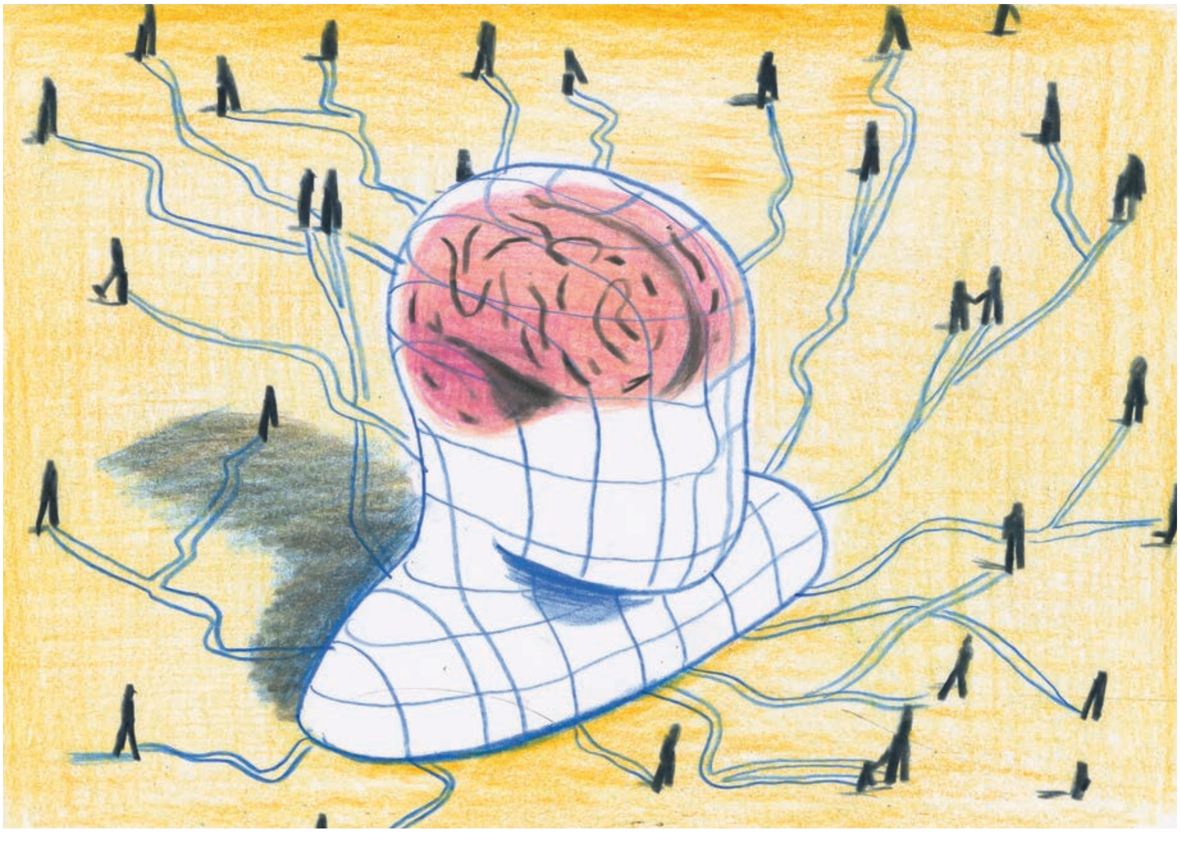
Soon after his departure from BGI, Wang formed ICX, knowing he would do something with AI and health. But he wasn't sure exactly what data besides DNA the company could, or should, collect. To figure it out, he met with a range of experts and companies, including a pivotal meeting in July 2016 at the Original Max's restaurant in Burlingame, California, near the San Francisco airport. In town pitching ICX to investors and prospective partners, Wang had arranged to see Jamie Heywood, the cofounder and chairman of PatientsLikeMe, who was visiting from Boston. As they sat in an orange-and-yellow plastic booth in the truck-stop-style café, it didn't take Heywood and Wang long to realize that they shared a fundamental exasperation with the limitations of today's medical practices. Giving people more data seemed like a promising route. PatientsLikeMe, which runs a service where thousands of members discuss their various chronic diseases in online forums and provide metrics about their health and the progression of their disease, had already shown the value of careful health tracking by individuals. Drinking coffee, Wang and Heywood dissed classic medical testing, which tends to be static, with one test taken at a time—an EKG in a clinical setting every year or two, for example, or when symptoms seem to warrant it. "We got excited about the possibility that we could discover the early stages of when a person shifts from good health to, say, becoming a diabetic," says Heywood, an MIT-trained engineer. "We both agreed that the technology is there, or is close to being there."

> "You also need millions of people – maybe as many as 10 million people – to get meaningful signals for common diseases."

Heywood, who is a fast-talking bundle of energy where Wang conveys a steady calm, suggested that such a profile should also include the sort of behavioral and personal data collected by his company. Information that people share in the forums of PatientsLikeMe—on such issues as the health impact of stress at work—provides valuable clues to other members on how they can better manage their chronic conditions. Why not help healthy people use similar tools and data? "It took about five minutes for Jun and I to realize that we could do this," he recalls.

Heywood brought something else to the table: his company had built a computer platform designed to analyze data reported by its half-million users. But it's not yet clear that combining all the data that ICX and its collaborators want to capture will be meaningful. Nor is it likely that AI will find significant correlations in the data unless ICX lures millions of people to its service—and even that many might not be enough. "ICX will struggle," predicts Eric Schadt of Sema4. "You also need millions of people—maybe as many as 10 million people—to get meaningful signals for common diseases."

Wang readily acknowledges the challenges. "To do everything we want will take many years," he says. When asked about the need to test large numbers of people to discern signals in the noise of all this data, he says that ICX is looking to enroll at least one million people in the next five years. "China has this big population, so I'm not worried about this," he says. He adds that as disposable income increases in China, people want to spend money on their health.



Wang admits, however, that he doesn't yet have a clear business plan. "I tend to think about the right thing to do with the science and the product first," he says. "Then I figure out the business model. Investors are okay with this. They don't want short term."

Smoke and mirrors?

Underlying ICX's challenge are also some fundamental questions about how to integrate artificial intelligence into health care. There's little doubt that advanced computing will eventually provide a huge boost toward making sense of all manner of health and biomedical data. And Wang is not the only one with business ambitions for the technology. According to CB Insights, which tracks venture capital investments, investors are funding 106 startups in AI and health—up from a handful a few years ago. They're pursuing everything from mental health and drug discovery to lifestyle management, virtual assistants, hospital management, and medical imaging and diagnostics. While this sounds impressive, AI so far has failed to make a substantial impact on most of medicine and health care. "In certain niches, AI is here and has been for years," says Marty Kohn, a physician and the former chief medical scientist at IBM, who helped develop IBM Watson Health. "But it's not happening at scale. And it hasn't yet helped large numbers of patients."

One reason is that it's incredibly difficult to interpret that much data. "I think AI has tremendous potential," says Leroy Hood, the president and cofounder of the Institute for Systems Biology in Seattle. "But the claims for AI and health care are very overblown." Most companies, he suggests, "don't do real science."

There's little doubt that advanced computing will eventually provide a huge boost toward making sense of all manner of health and biomedical data.

A longtime pioneer in finding tools for understanding the body's complex functions, Hood is a cofounder of Seattle-based Arivale, another health data company. In 2014, Arivale started offering its own version of lifestyle, wellness, and molecular testing, coupled with personal coaching. In July 2017, Hood and Arivale published a small study in *Nature Biotechnology* that he says provides a proof-of-concept analysis of what the researchers call "personal, dense, dynamic data clouds" measured in healthy people over time. They used advanced algorithms to make correlations for 108 subjects who took dozens of health tests and measurements. Some of the participants learned that they had vitamin deficiencies; others found they had early signs of inflammatory bowel disease or diabetes that needed tending through diet or supplements. These results, however, are preliminary, and far more of them will be needed to separate real findings from the firehose of data.

As for Wang, he is experimenting on himself with still more ways to acquire such information. As he continues his tour of ICX's headquarters in Shenzhen, he points to a toilet just off his office where he collects plastic bags of poop for his daily microbiome analysis. Wang describes plans to build a "smart toilet" that will capture and analyze one's waste and feed it into an AI-generated personal profile. "We have the technology to do this," he says. "We have the algorithms. It will be cheap, something like $200." Wang next lifts up his sky-blue polo shirt to show off a wireless continuous heart-rate monitor.

One wonders, however, if millions of healthy people will be as obsessed as Jun Wang is with collecting so much data on themselves. The question seems to take him by surprise, momentarily roiling his composure. He knits his brow, looking as if he can't imagine that other people might not want smart mirrors and toilets, frequent blood draws to measure thousands of metabolites, and heart monitors taped to their chests. "I'm not asking everyone to do this," he finally says. "People choose not to know a lot of things. But there are plenty of people who want to know, or can be educated to want to know." He pauses for another nanosecond and then flashes that smile, looking as if he had just figured out the answer to this literally multibillion-dollar question about his effort and his company. "People used to not want to know their genes; now more and more people want to know," he says. "I'm sure that this trend will continue."

David Ewing Duncan is a life science journalist and author of Experimental Man*, and the CEO of Arc Fusion.*

How to Root Out Hidden Biases in AI

Algorithms are making life-changing decisions like denying parole or granting loans. Cynthia Dwork, a computer scientist at Harvard, is developing ways of making sure the machines are operating fairly.

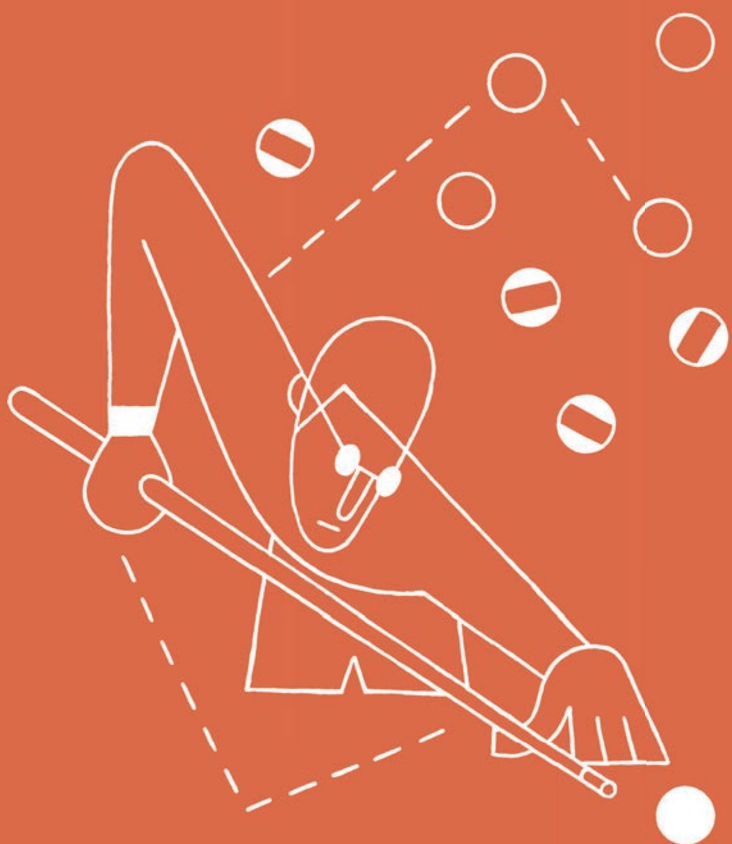
Why is it hard for algorithm designers or data scientists to account for bias and unfairness?

Take a work environment that's hostile to women. Suppose that you define success as the fact that someone holds a job for two to three years and gets a promotion. Then your predictor—based on the historical data—will accurately predict that it's not a good idea to hire women. What's interesting here is that we're not talking about historical hiring decisions. Even if the hiring decisions were totally unbiased, the reality—the real discrimination in the hostile environment—persists. It's deeper, more structural, more ingrained and harder to overcome.

I believe the great use for machine learning and AI will be in conjunction with really knowledgeable people who know history and sociology and psychology to figure out who should be treated similarly to whom.

I'm not saying computers will never be able to do it, but I don't see it now. How do you know when you have the right model, and when it's capturing what really happened in society? You need to have an understanding of what you're talking about. There's the famous saying "All models are wrong and some are useful."

—as told to Will Knight

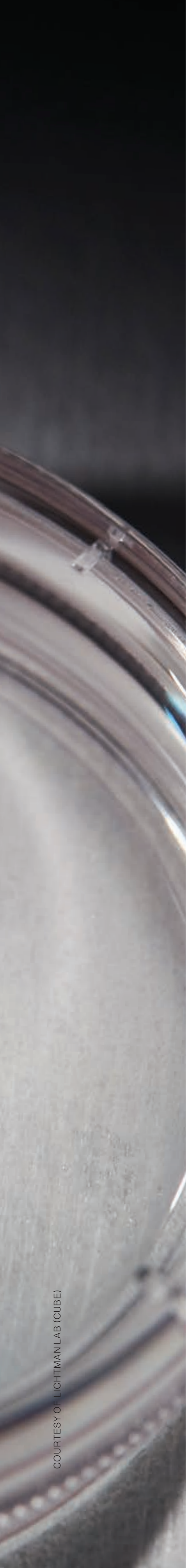


MIGUEL PORLAN

Inside the Moonshot Effort to Finally

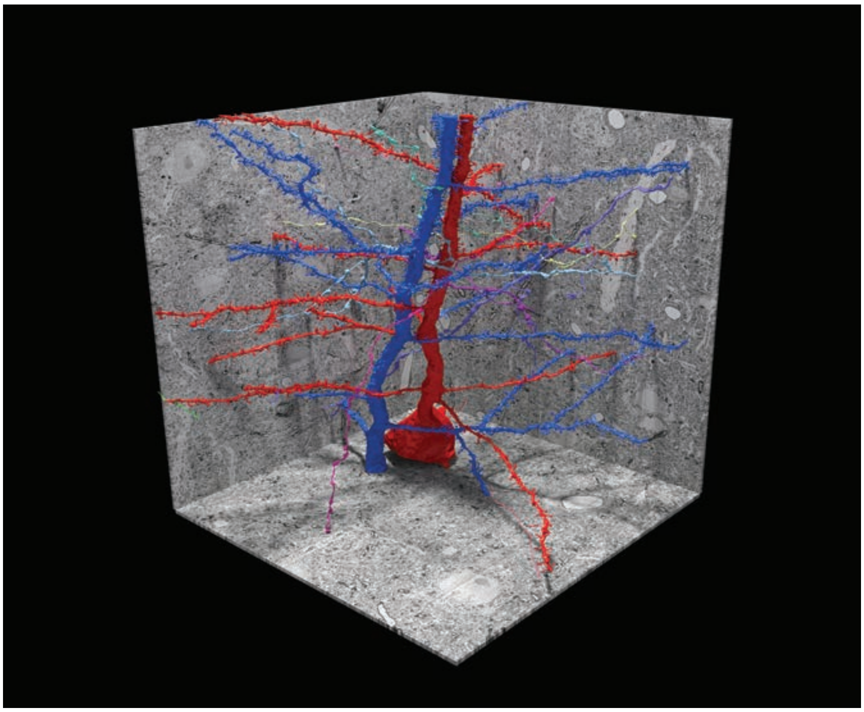
Figure Out

the Brain

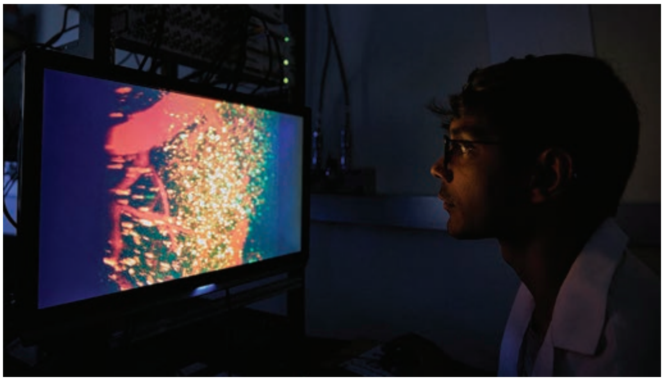


AI is only loosely modeled on the brain. So what if you wanted to do it right? You'd need to do what has been impossible until now: map what actually happens in neurons and nerve fibers.

by M. Mitchell Waldrop
Photographs by Ken Richardson



COURTESY OF LICHTMAN LAB (CUBE)



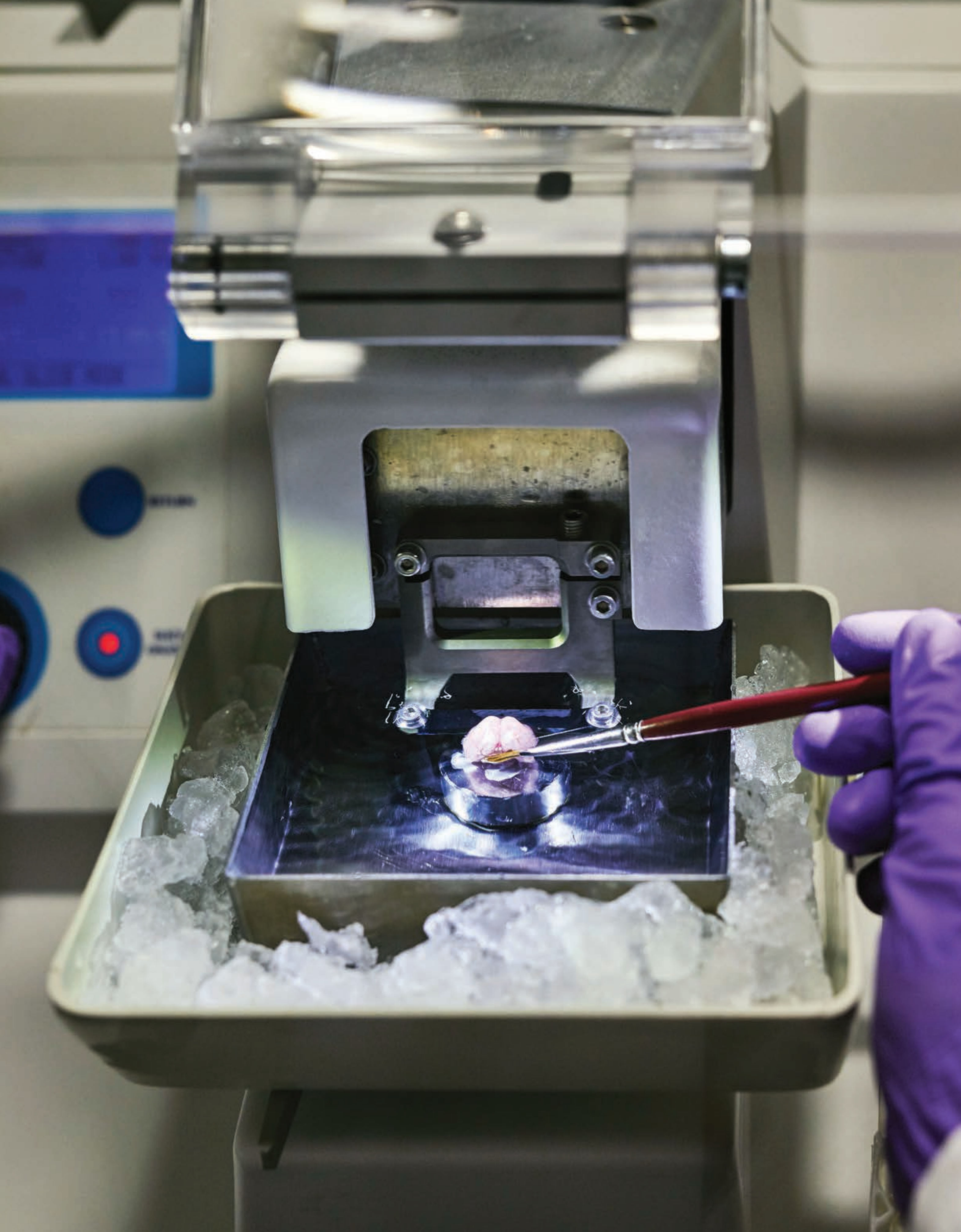
Here's the problem with artificial intelligence today,

says David Cox. Yes, it has gotten astonishingly good, from near-perfect facial recognition to driverless cars and world-champion Go-playing machines. And it's true that some AI applications don't even have to be programmed anymore: they're based on architectures that allow them to learn from experience.

Yet there is still something clumsy and brute-force about it, says Cox, a neuroscientist at Harvard. "To build a dog detector, you need to show the program thousands of things that are dogs and thousands that aren't dogs," he says. "My daughter only had to see one dog"—and has happily pointed out puppies ever since. And the knowledge that today's AI does manage to extract from all that data can be oddly fragile. Add some artful static to an image—noise that a human wouldn't even notice—and the computer might just mistake a dog for a dumpster. That's not good if people are using facial recognition for, say, security on smartphones. (See "Is AI Riding a One-Trick Pony?" on page 28.)

To overcome such limitations, Cox and dozens of other neuroscientists and machine-learning experts joined forces last year for the Machine Intelligence from Cortical Networks (MICrONS) initiative: a $100 million effort to reverse-engineer the brain. It will be the neuroscience equivalent of a moonshot, says Jacob Vogelstein, who conceived and launched MICrONS when he was a program officer for the Intelligence Advanced Research Projects Agency, the U.S. intelligence community's research arm. (He is now at the venture capital firm Camden Partners in Baltimore.) MICrONS researchers are attempting to chart the function and structure of every detail in a small piece of rodent cortex.

Previous pages: *A rat brain in a dish and a rendering of two neurons with spiny dendrites.* ***This page, top:*** *A technician observes the brain of a live rat during a test.* ***Bottom:*** *After the test, the animal's brain has been removed.* ***Opposite page:*** *The brain is glued to a plate before being scanned.*



It's a testament to the brain's complexity that a moonshot is needed to map even this tiny piece of cortex, a cube measuring one millimeter on a side—the size of a coarse grain of sand. But this cube is thousands of times bigger than any chunk of brain anyone has tried to detail. It will contain roughly 100,000 neurons and something like a billion synapses, the junctions that allow nerve impulses to leap from one neuron to the next.

It's an ambition that leaves other neuroscientists awestruck. "I think what they are doing is heroic," says Eve Marder, who has spent her entire career studying much smaller neural circuits at Brandeis University. "It's among the most exciting things happening in neuroscience," says Konrad Kording, who does computational modeling of the brain at the University of Pennsylvania.

The ultimate payoff will be the neural secrets mined from the project's data—principles that should form what Vogelstein calls "the computational building blocks for the next generation of AI." After all, he says, today's neural networks are based on a decades-old architecture and a fairly simplistic notion of how the brain works. Essentially, these systems spread knowledge across thousands of densely interconnected "nodes," analogous to the brain's neurons. The systems improve their performance by adjusting the strength of the connections. But in most computer neural networks the signals always cascade forward, from one set of nodes to the next. The real brain is full of feedback: for every bundle of nerve fibers conveying signals from one region to the next, there is an equal or greater number of fibers coming back the other way. But why? Are those feedback fibers the secret to one-shot learning and so many other aspects of the brain's immense power? Is something else going on?

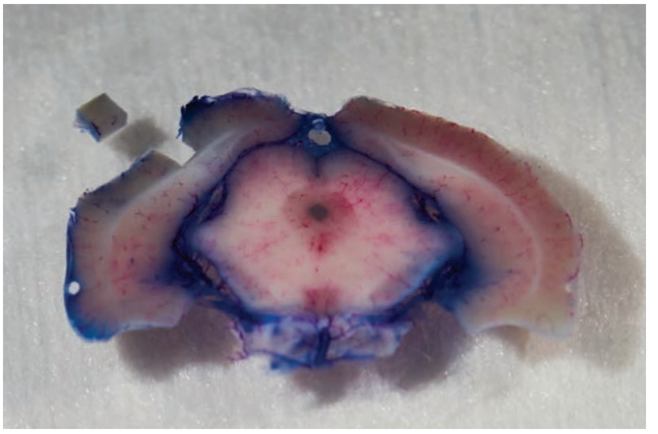
MICrONS should provide at least some of the answers, says Princeton University neuroscientist Sebastian Seung, who is playing a key role in the mapping effort. In fact, he says, "I don't think we can answer these questions without a project like this."

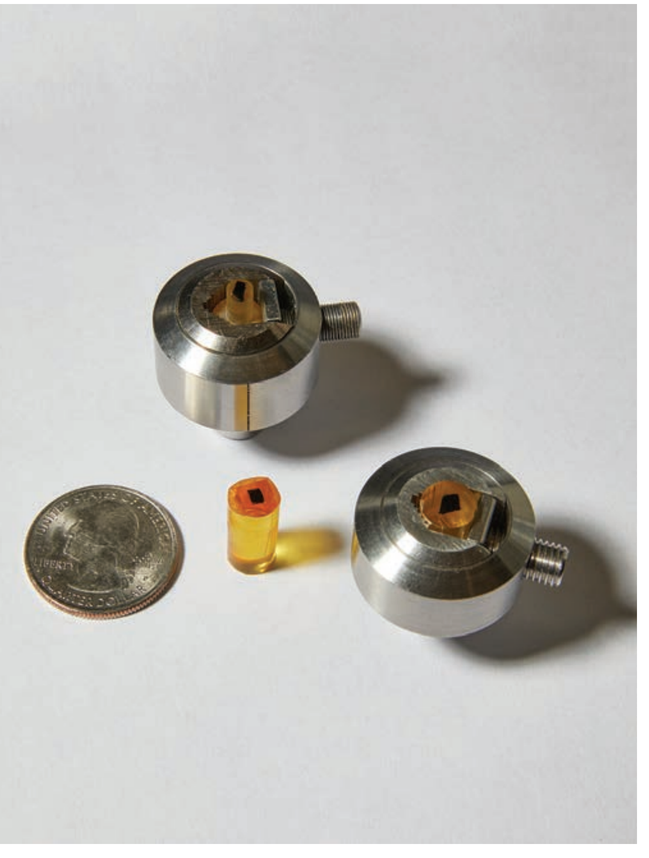
Zooming in

The MICrONS teams—one led by Cox, one based at Rice University and the Baylor College of Medicine, and a third at Carnegie Mellon—are each pursuing something that is remarkably comprehensive: a reconstruction of all the cells in a cubic millimeter of a rat's brain, plus a wiring diagram—a "connectome"—showing how every cell is connected to every other cell, and data showing exactly which situations make neurons fire and influence other neurons.

The first step is to look into the rats' brains and figure out what neurons in that cubic millimeter are actually doing. When the animal is given a specific visual stimulus, such as a line oriented a certain way, which neurons suddenly start firing off impulses, and which neighbors respond?

As recently as a decade ago, capturing that kind of data ranged from difficult to impossible: "The tools just never





Top: *The small cube in the upper left is the portion of the brain that will be mapped.* ***Bottom:*** *That piece of the brain is encased in acrylic in preparation for being sliced extremely thin.*

existed," Vogelstein says. It's true that researchers could slide ultrathin wires into the brain and get beautiful recordings of electrical activity in individual neurons. But they couldn't record from more than a few dozen at a time because the cells are packed so tightly together. Researchers could also map the overall geography of neural activity by putting humans and other animals in MRI machines. But researchers couldn't monitor individual neurons that way: the spatial resolution was about a millimeter at best.

What broke that impasse was the development of techniques for making neurons light up when they fire in a living brain. To do it, scientists typically seed the neurons with fluorescent proteins that glow in the presence of calcium ions, which surge in abundance whenever a cell fires. The proteins can be inserted into a rodent's brain chemically, carried in by a benign virus, or even encoded into the neurons' genome. The fluorescence can then be triggered in several ways—perhaps most usefully, by a pair of lasers that pump infrared light into the rat through a window set into its skull. The infrared frequencies allow the photons to penetrate the comparatively opaque neural tissue without damaging anything, before getting absorbed by the fluorescent proteins. The proteins, in turn, combine the energy from two of the infrared photons and release it as a single visible-light photon that can be seen under an ordinary microscope as the animal looks at something or performs any number of other actions.

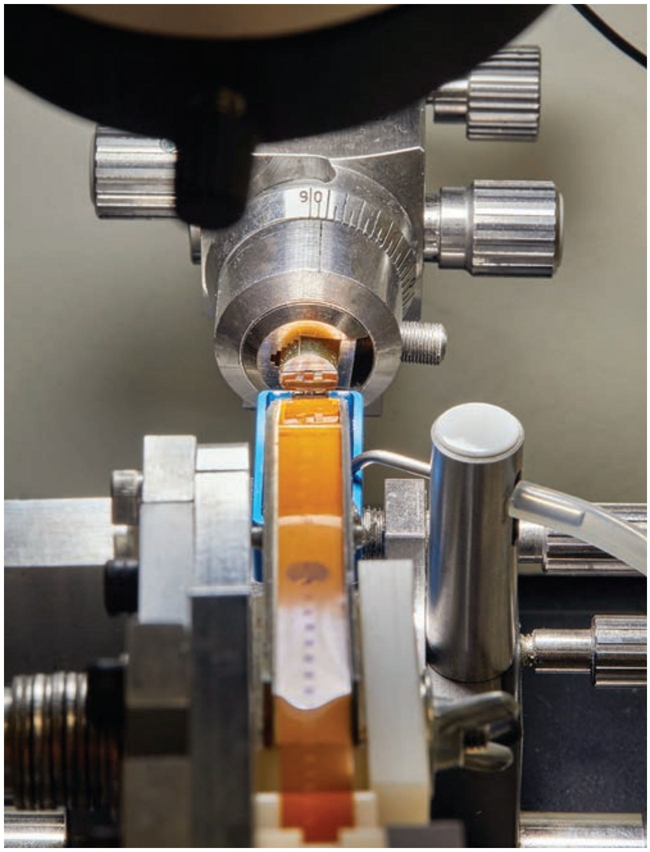
Andreas Tolias, who leads part of the team at Baylor, says this is "revolutionary" because "you can record from every single neuron, even those that are right next to one another."

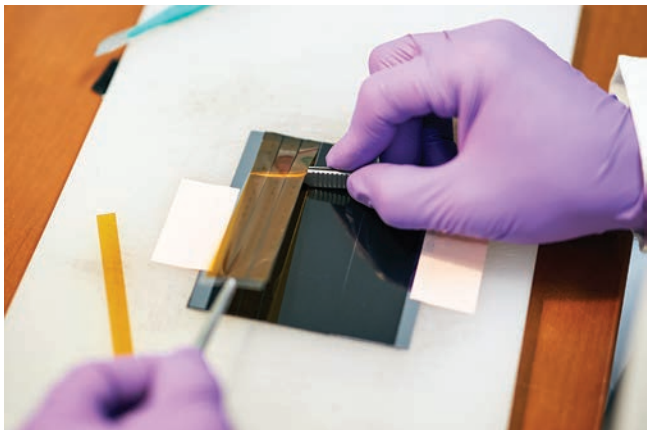
Once a team in Cox's lab has mapped a rat's neural activity, the animal is killed and its brain is infused with the heavy metal osmium. Then a team headed by Harvard biologist Jeff Lichtman cuts the brain into slices and figures out exactly how the neurons are organized and connected.

That process starts in a basement lab with a desktop machine that works like a delicatessen salami slicer. A small metal plate rises and falls, methodically carving away the tip of what seems to be an amber-colored crayon and adhering the slices to a conveyor belt made of plastic tape. The difference is that the "salami" is actually a tube of hard resin that encases and supports the fragile brain tissue, the moving plate contains an impossibly sharp diamond blade, and the slices are about 30 nanometers thick.

Next, at another lab down the hall, lengths of tape containing several brain slices each are mounted on silicon wafers and placed inside what looks like a large industrial refrigerator. The device is an electron microscope: it uses 61 electron beams to scan 61 patches of brain tissue simultaneously at a resolution of four nanometers.

Each wafer takes about 26 hours to scan. Monitors next to the microscope show the resulting images as they build





Top: *The cut slices of brain stick to a plastic tape.* ***Bottom:*** *The tape, with brain samples attached, is trimmed and put on a slide plate that will go into a huge scanning machine.*

up in awe-inspiring detail—cell membranes, mitochondria, neurotransmitter-filled vesicles crowding at the synapses. It's like zooming in on a fractal: the closer you look, the more complexity you see.

Slicing is hardly the end of the story. Even as the scans come pouring out of the microscope—"You're sort of making a movie where each slice is deeper," says Lichtman—they are forwarded to a team led by Harvard computer scientist Hanspeter Pfister. "Our role is to take the images and extract as much information as we can," says Pfister.

That means reconstructing all those three-dimensional neurons—with all their organelles, synapses, and other features—from a stack of 2-D slices. Humans could do it with paper and pencil, but that would be hopelessly slow, says Pfister. So he and his team have trained neural networks to track the real neurons. "They perform a lot better than all the other methods we've used," he says.

Each neuron, no matter its size, puts out a forest of tendrils known as dendrites, and each has another long, thin fiber called an axon for transmitting nerve impulses over long distances—completely across the brain, in extreme cases, or even all the way down the spinal cord. But by mapping a cubic millimeter as MICrONS is doing, researchers can follow most of these fibers from beginning to end and thus see a complete neural circuit. "I think we'll discover things," Pfister says. "Probably structures we never suspected, and completely new insights into the wiring."

The power of anticipation

Among the questions the MICrONS teams hope to begin answering: What are the brain's algorithms? How do all those neural circuits actually work? And in particular, what is all that feedback doing?

Many of today's AI applications don't use feedback. Electronic signals in most neural networks cascade from one layer of nodes to the next, but generally not backward. (Don't be thrown by the term "backpropagation," which is a way to *train* neural networks.) That's not a hard-and-fast rule: "recurrent" neural networks do have connections that go backward, which helps them deal with inputs that change with time. But none of them use feedback on anything like the brain's scale. In one well-studied part of the visual cortex, says Tai Sing Lee at Carnegie Mellon, "only 5 to 10 percent of the synapses are listening to input from the eyes." The rest are listening to feedback from higher levels in the brain.

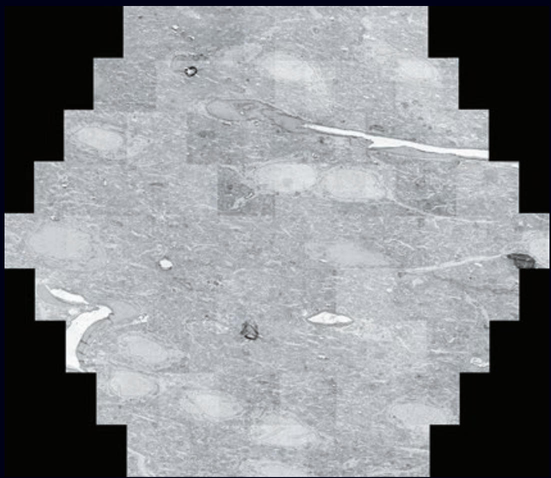
There are two broad theories about what the feedback is for, says Cox, and "one is the notion that the brain is constantly trying to predict its own inputs." While the sensory cortex is processing *this* frame of the movie, so to speak, the higher levels of the brain are trying to anticipate the *next* frame, and passing their best guesses back down through the feedback fibers.

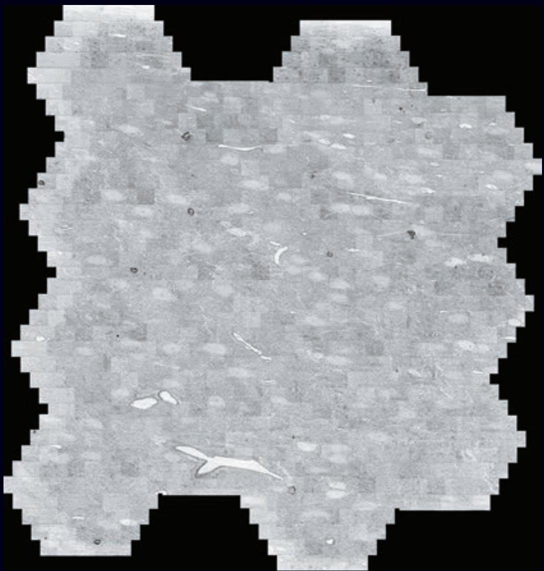
This the only way the brain can deal with a fast-moving environment. "Neurons are really slow," Cox says. "It can take up to 170 to 200 milliseconds to go from light hitting the retina through all the stages of processing up to the level of conscious perception. In that time, Serena Williams's tennis serve travels nine meters." So anyone who manages to return that serve must be swinging her racket on the basis of prediction.

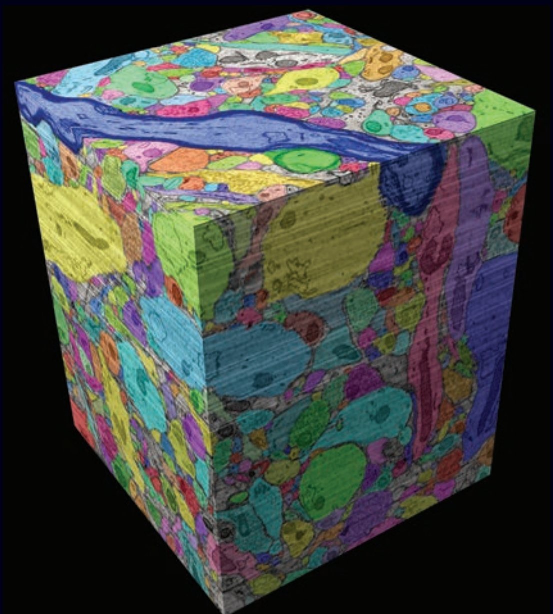
And if you're constantly trying to predict the future, Cox says, "then when the real future arrives, you can adjust to make your next prediction better." That meshes well with the second major theory being explored: that the brain's feedback connections are there to guide learning. Indeed, computer simulations show that a struggle for improvement forces any system to build better and better models of the world. For example, Cox says, "you have to figure out how a face will appear if it turns." And that, he says, may turn out to be a critical piece of the one-shot-learning puzzle.

"When my daughter first saw a dog," says Cox, "she didn't have to learn about how shadows work, or how light bounces off surfaces." She had already built up a rich reservoir of experience about such things, just from living in the world. "So

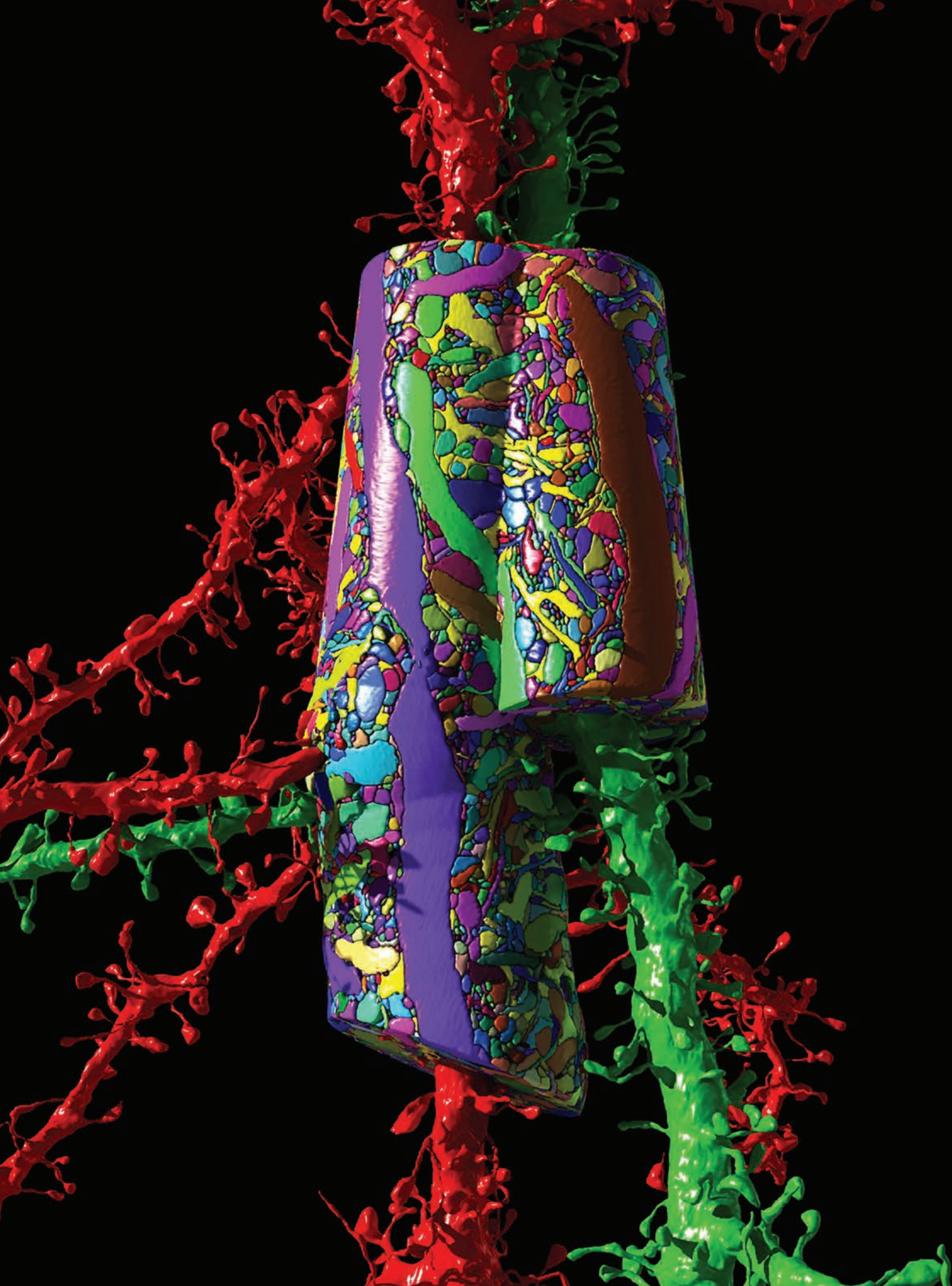
Opposite page, top row: *Scans of brain slices are stitched together by an algorithm.* ***Middle row:*** *A "multibeam field of view," made of 61 images taken by the electron microscope, is seen at left; 14 multibeam fields of view are combined at right.* ***Bottom row:*** *Scans are assembled into a cube and colorized.*







COURTESY OF LICHTMAN LAB



COURTESY OF LICHTMAN LAB

when she got to something like 'That's a dog,'" he says, "she could add that information to a huge body of knowledge."

If these ideas about the brain's feedback are correct, they could show up in MICrONS's detailed map of a brain's form and function. The map could demonstrate what tricks the neural circuitry uses to implement prediction and learning. Eventually, new AI applications could mimic that process.

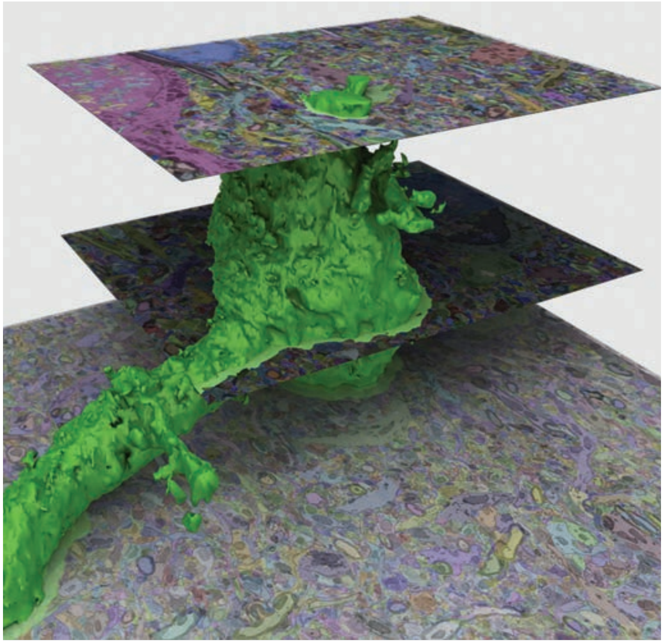
Even then, however, we will remain far from answering all the questions about the brain. Knowing neural circuitry won't teach us everything. There are forms of cell-to-cell communication that don't go through the synapses, including some performed by hormones and neurotransmitters floating in the spaces between the neurons. There is also the issue of scale. As big a leap as MICrONS may be, it is still just looking at a tiny piece of cortex for clues about what's relevant to computation. And the cortex is just the thin outer layer of the brain. Critical command-and-control functions are also carried out by deep-brain structures such as the thalamus and the basal ganglia.

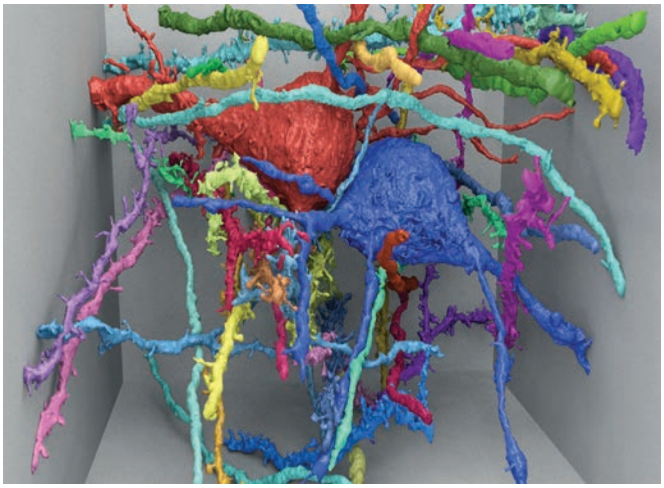
The good news is that MICrONS is already paving the way for future projects that map larger sections of the brain.

Much of the $100 million, Vogelstein says, is being spent on data collection technologies that won't have to be invented again. At the same time, MICrONS teams are developing faster scanning techniques, including one that eliminates the need to slice tissue. The Carnegie Mellon group, working with teams at Harvard, MIT, and the Woods Hole Oceanographic Institution, has devised a way to uniquely label each neuron with a "bar-coding" scheme and then view the cells in great detail by saturating them with a special gel that very gently inflates them to dozens or hundreds of times their normal size.

"So the first cubic millimeter will be hard to collect," Vogelstein says, "but the next will be much easier."

M. Mitchell Waldrop is a freelance writer in Washington, D.C. He is the author of Complexity *and* The Dream Machine *and was formerly an editor at* Nature.



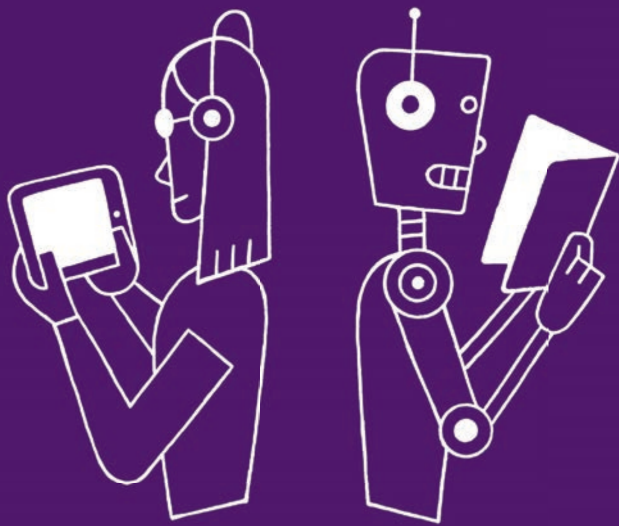


COURTESY OF PFISTER LAB

***On these pages:** The colorized cubes are useful in 3-D illustrations of various neuronal structures and processes, giving scientists their most detailed map yet of what actually happens in the brain.*

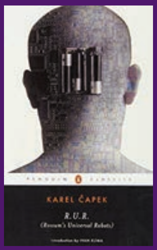
Fiction That Gets AI Right

Even the most futuristic applications of AI, from robotic servants to instant health scans, somehow already seem familiar because they have been endless fodder for pop culture. At the movies, you've probably seen artificial intelligence as a menace in *The Terminator* or *2001: A Space Odyssey;* as a near-destroyer of the world in *WarGames;* as our master in *The Matrix;* or as a companion (as in *Her* and in the Stanley Kubrick–Steven Spielberg combination that was called *A.I. Artificial Intelligence*). But many lesser-known stories, plays, TV shows, and films stand out as well for their perceptiveness about how sophisticated AI will affect us. Here are a few suggestions. —*Brian Bergstein*



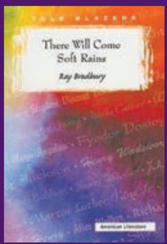
The Machine Stops, BY E.M. FORSTER, 1909
This short story takes place in a future chillingly akin to the Singularity as envisioned by Ray Kurzweil, except here it's the final step before the end of the world rather than the epitome of computer-assisted enlightenment. Everyone sits alone in an underground room, listening to lectures from, or giving lectures to, friends who are always remote; they appear to each other in something like holograms, because life is now only about the endless discussion of ideas rather than physical experience. The Machine takes care of all their other needs—for a time, at least.

Humanity, in its desire for comfort, had over-reached itself. It had exploited the riches of nature too far. Quietly and complacently, it was sinking into decadence, and progress had come to mean the progress of the Machine.



R.U.R. (Rossum's Universal Robots), BY KAREL CAPEK, 1920
This play introduced "robot" into the language, from the Czech word "robota," which means "forced labor." It's all about the hubris of a factory owner unable to resist the temptation to automate as much labor as possible—until the "artificial people" he creates turn on him and the rest of humanity.

"'Robots of the world! We, the first union at Rossum's Universal Robots, declare that man is our enemy and the blight of the universe.' Who the hell taught them to use phrases like that?"



There Will Come Soft Rains, BY RAY BRADBURY, 1950
A smart home in post-apocalypse 2026 has outlived its human occupants but still cooks for them and tries to guide them through their daily routines.

"Mrs. McClellan, which poem would you like this evening?" The house was silent. The voice said at last, "Since you express no preference, I shall select a poem at random."

Humans, DEBUTED IN 2015
Imagine the world of today, except that artificial people called Synths handle the drudgery in factories, farm fields, and homes. This TV series is gripping because it explores the implications on many levels. How does robotic labor erode humans' motivation and sense of purpose? And what if some of these Synths can feel and think for themselves? There's a whiff of *R.U.R.* to it, and in fact a character who illegally hacks robots has the last name of Capek.

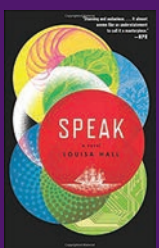
Hobb: "Robert, these machines are conscious."

Robert: "How do you know they don't just simulate it?"

Hobb: "How do we know you don't?"

Chappie, 2015
Unlike a machine encoded with the Three Laws of Robotics in Isaac Asimov's stories, the police droid named Chappie in this movie doesn't know from the start how to behave. He has to learn right and wrong by observing the world. That childlike innocence becomes problematic when he gets stolen by two gangsters who try to use him for crime. As Gary Marcus, a psychologist and AI entrepreneur, wrote in the *New Yorker,* "*Chappie* can be seen an impassioned plea for moral education, not just for humans but for our future silicon-based companions."

"Chappie, in life, lots of people will tell you what you can't do. And you know what, you must never listen."



Speak, BY LOUISA HALL, 2015
The recollections of an AI doll creator and four other characters—who all live at different points in time from 1663 to 2040—are interwoven in this novel to explore fundamental similarities between human and computer intelligence, memory, and expression. (For more by Hall, see "How We Feel About Robots That Feel," page 74.)

Ramona learned for the sake of her doll. She ran with her doll so her doll could feel movement. The two of them never fought. They were perfect for each other. My daughter's doll was a softly blurred mirror that I held up to her face.

MIGUEL PORLAN

中国人工智能的崛起

LINTAO ZHANG/GETTY

China's AI Awakening

The West shouldn't fear China's artificial-intelligence revolution. It should copy it.

By Will Knight

On a tropical island that marks the southern tip of China, a computer program called Lengpudashi is playing one-on-one poker against a dozen people at once, and it's absolutely crushing them. Lengpudashi, which means "cold poker master" in Mandarin, is using a new artificial-intelligence technique to outbet and outbluff its opponents in a two-player version of Texas hold 'em.

The venue for the tournament is a modern-looking technology park in Haikou, capital of the island of Hainan. Outside, modern high-rises loom over aging neighborhoods. Those gathered to play the machine include several poker champs, some well-known Chinese investors, entrepreneurs, and CEOs, and even the odd television celebrity. The games are being broadcast online, and millions are watching. The event symbolizes a growing sense of excitement and enthusiasm for artificial intelligence in China, but there's also a problem. Lengpudashi wasn't made in Hainan, Beijing, or Shanghai; it was built in Pittsburgh, U.S.A.

For many in China, this simply won't do. The country is now embarking on an unprecedented effort to master artificial intelligence. Its government is planning to pour hundreds of billions of yuan (tens of billions of dollars) into the technology in coming years, and companies are investing heavily in nurturing and developing AI talent. If this country-wide effort succeeds—and there are many signs it will—China could emerge as a leading force in AI, improving the productivity of its industries and helping it become leader in creating new businesses that leverage the technology. And if, as many believe, AI is the key to future growth, China's prowess in the field will help fortify its position as the dominant economic power in the world.

Indeed, the country's political and business leaders are betting that AI can jump-start its economy. In recent decades, a booming manufacturing sector—and market reforms encouraging foreign trade and investment—have helped bring hundreds of millions of people out of poverty, creating business empires and transforming Chinese society. But manufacturing growth is slowing, and the country is looking toward a future built around advanced technology (see "China Is Building a Robot Army of Model Workers," May/June 2016). Applying artificial intelligence may be the next step in this technology-fueled economic miracle. While many in the West fret about AI eliminating jobs and worsening wealth and income inequality, China seems to believe it can bring about precisely the opposite outcomes.

China's AI push includes an extraordinary commitment from the government, which recently announced a sweeping vision for AI ascendancy. The plan calls for homegrown AI to match that developed in the West within three years, for China's researchers to be making "major breakthroughs" by 2025, and for Chinese AI to be the envy of the world by 2030.

There are good reasons to believe the country can make this vision real. In the early 2000s, the government said it wanted to build a high-speed rail network that would spur technological development and improve the country's transportation system. This train network is now the most advanced in the world. "When the Chinese government announces a plan like this, it has significant implications for the country and the economy," says Andrew Ng, a prominent AI expert who previously oversaw AI technology and strategy at China's biggest online search company, Baidu. "It's a very strong signal to everyone that things will happen."

The government's call to action will accelerate what has already begun to happen. The country's tech companies, led by the Internet giants Baidu, Alibaba, and Tencent, are hiring scores of AI experts, building new research centers, and investing in data centers that rival anything operated by Amazon, Google, or Microsoft. Money is also pouring into countless startups as Chinese entrepreneurs and investors spy a huge opportunity to harness AI in different industries.

China has some big advantages in AI. It has a wealth of talented engineers and scientists, for one. It also is rich in the data necessary to train AI systems. With fewer obstacles to data collection and use, China is amassing huge databases that don't exist in other countries. The results can be seen in the growth of facial-recognition systems based on machine learning: they now identify workers at offices and customers in stores, and they authenticate users of mobile apps.

The nationwide interest in the poker tournament in Hainan reflects China's appetite for the latest artificial-intelligence breakthroughs. Mastering even a two-player form of poker is a significant achievement for AI because, unlike many other games, poker requires players to act with limited information, and to sow uncertainty by behaving unpredictably. An optimal strategy therefore requires both careful and instinctive judgment, which are not easy qualities to give a machine. Lengpudashi impressively solved the problem by using a brilliant new game-theory algorithm, which could be very useful in many other scenarios, including financial trading and business negotiations. But Lengpudashi has received far less attention in its home country than it has in Hainan.

To explore China's AI revolution and its implications, I've traveled to the heart of this boom and met with many of the key researchers, entrepreneurs, and executives. From China's bustling capital to its factory-filled south, and from an ambitious new research center to a billion-dollar startup, one

Kai-Fu Lee is CEO of the venture capital firm Sinovation Ventures.

GREG BAKER/GETTY

thing is clear: artificial intelligence may have been invented in the West, but you can see its future taking shape on the other side of the world.

看东方
LOOK EAST

My journey begins at MIT, one of the wellsprings of artificial intelligence. Kai-Fu Lee, a well-known Chinese AI expert and investor and one of the organizers of the Hainan tournament, has come to recruit students for a new AI institute that his company, Sinovation Ventures, is building in Beijing.

Lee gives a talk entirely in Mandarin to an auditorium packed with about 300 Chinese students. He is dressed impeccably, in an expensive-looking suit and dress shirt, and he speaks in a confident, soothing tone. The talk touches on the interwoven trends that have driven the recent rise in machine intelligence: more powerful computers, ingenious new algorithms, and huge quantities of data. He argues that China is perfectly poised to take advantage of these advances.

"The U.S. and Canada have the best AI researchers in the world, but China has hundreds of people who are good, and way more data," he tells the audience. "AI is an area where you need to evolve the algorithm and the data together; a large amount of data makes a large amount of difference."

In 1998 Lee founded Microsoft's Beijing research lab, which showcased the country's exciting talent pool (see "An Age of Ambition," June 2004). Then, in 2005, he became the founding president of Google China. Lee is now famous for mentoring young entrepreneurs, and he has more than 50 million followers on the Chinese microblogging platform Sina Weibo.

In the audience are exactly the type of prized students who would normally flock to Silicon Valley. But many are clearly taken by Lee's message of opportunities in China. The crowd hangs on his every word, and some people clamor for autographs afterward. "Today the U.S. has a technology leadership," Lee tells me later. "But China has a tremendous amount of potential."

To see what this potential looks like up close, I travel to Lee's new institute, half a world away from MIT, in Beijing's Haidian district. The streets outside are filled with people on colorful ride-sharing bikes. I pass lots of fashionable-looking young techies as well as people delivering breakfast—ordered via smartphone, no doubt—to busy workers. At the time of my visit, a major AI event is taking place a few hundred miles to the south in Wuzhen, a picturesque town of waterways. AlphaGo, a program developed by researchers at the Alphabet subsidiary DeepMind, is playing the ancient board game Go against several top Chinese players, including the world's number one, Ke Jie. And it's soundly beating them.

AlphaGo's victories in Wuzhen are followed closely in the Chinese capital. As I enter Sinovation's institute, in fact, I notice a Go board on which engineers are testing out the moves made during some of the matches.

The location of the institute is well chosen. From the office windows, you can see the campuses of both Peking University and Tsinghua University, two of China's top academic institutions. Sinovation provides machine-learning tools and data sets to train Chinese engineers, and it offers expertise for companies hoping to make use of AI. The institute has about 30 full-time employees so far, but the plan is to employ more than 100 by next year, and to train hundreds of AI experts each year through internships and boot camps. Right now, roughly 80 percent of the institute's funding and projects are aimed at commercializing AI, while the rest is focused on more far-out technology research and startup incubation.

The goal isn't to invent the next AlphaGo, though; it's to upgrade thousands of companies across China using AI. Lee says many Chinese businesses, including the big state-owned enterprises, are technologically backward and ripe for overhaul, but they lack any AI expertise themselves. Needless to say, this presents an enormous opportunity.

人工智能无处不在
AI EVERYWHERE

Across the capital, in fact, I notice a remarkable amount of interest in artificial intelligence. In one restaurant, for instance, I find a machine that takes my picture and then supposedly uses AI to determine how healthy I am. This seems completely impossible, but the machine says I'm in great shape before suggesting that I have plenty to eat.

This fascination with the technology is reflected in Beijing's feverish startup scene, which is already producing some formidable AI companies. One of them is SenseTime, which was founded in 2014 and is already among the world's most valuable AI startups. Launched by researchers from the Chinese University of Hong Kong, SenseTime provides computer-vision technology to big Chinese companies, including the state-owned cellular provider China Mobile and the online retail giant JD.com. The company is now studying markets such as automotive systems. This July, SenseTime raised $410 million in funding, giving it a valuation of $1.5 billion. The entrance to SenseTime's office features several large screens fitted with cameras. One can automatically add augmented-reality effects to a person's face. Snapchat and Instagram offer similar gimmicks, but this one can also add effects in response to hand and body movements as well as smiles or winks.

Qing Luan, director of SenseTime's augmented-reality group, previously developed office apps for Microsoft in Redmond, Washington. She says she returned to China because the opportunities just seemed much bigger. "We were struggling to get a thousand users; then I talked with my friend who was working at a startup in China, and she said, 'Oh, a million users is nothing—we get that in several days,'" she recalls.

Earlier this year SenseTime's engineers developed a novel image-processing technique for automatically removing smog and rain from photographs, and another for tracking full-body motion using a single camera. Last year they were part of a team that won a prestigious international computer-vision award.

Xiaoou Tang, SenseTime's founder and a professor at the Chinese University of Hong Kong, is wearing a suede jacket, slacks, and glasses, and he has an intense air about him. He seems fiercely proud of his company's achievements. Tang explains that the company's name comes from a phonetic transcription of the name of the Shang dynasty and of its first ruler, Tang. This era, beginning around 1600 BCE, was a critical age of development for the country. "China was leading the world then," Tang says with a smile. "And in the future, we will lead again with technological innovations."

中国曾经领先于世界

"China was leading the world then.

智能制造
MANUFACTURING INTELLIGENCE

In the United States and other Western nations, many large sectors, such as manufacturing and services, have been slow to invest in AI and change their business practices. In China, there appears to be a greater sense of urgency about adapting to the changing technology. Across just about every industry, Chinese companies are shrugging off their reputation for following Western businesses, and investing heavily in research and development. Ng, who previously led Baidu's AI effort, says China's business leaders understand better than most the need to embrace new trends. "The titans of industry [in China] have seen fortunes made and fortunes lost all within their lifetime," he says. "When you see the tech trends shift, you had better move quickly, or someone else will beat you."

Baidu anticipated the potential of artificial intelligence and sought to leverage it to reinvent its whole business. In 2014, the company created a lab dedicated to applying deep learning across its business, and in recent years, its researchers have made some significant advances. When Microsoft developed a system capable of better-than-human performance in speech recognition last year, for instance, few Western reporters realized that Baidu had done that a year earlier.

Following Baidu's example, other Chinese tech companies are also looking to reinvent themselves with AI. The Internet leader Tencent, headquartered in the city of Shenzhen, is among them.

未来我们将再次成为领导者

And in the future, we will lead again."

Shenzhen is nestled next to Hong Kong in southern China. Approaching by air, I see an armada of cargo ships moored in the South China Sea. In 1980, when Shenzhen was a small market town, it was designated China's first Special Economic Zone, granting it unprecedented economic and regulatory freedoms. Manufacturing empires were built on the backs of migrant workers producing every imaginable product, and the population rose from 30,000 to more than 11 million. In recent years, the city has reflected China's technological progress, and it is now home to global technology companies including the networking giant Huawei, the smartphone maker ZTE, and the electric-car company BYD.

The city's main strip is lined with palm trees, gaudy hotels, and busy bars and restaurants. Tencent's headquarters, in Nanshan district, spans several large buildings, and the entrance is as busy as a subway station. Stepping inside, out of stifling humidity, I begin a tour that touts Tencent's history and achievements. And it shows that you don't have to be first in a technology to have a big impact. In 2011, the company launched a simple messaging app, modeled on products already found in the U.S. This would evolve into WeChat, an innovative mobile platform that now supports social networking, news, games, and mobile payments. With 889 million daily active users, WeChat now has an incredible grip on China's Internet market.

Although Tencent created an AI lab only last year, it has hired scores of researchers and opened an outpost in Seattle. The company's researchers have already copied AI innovations from the West, including DeepMind's AlphaGo. Tencent's AI lab is led by Tong Zhang, a quiet man with thin glasses and a round face, who previously worked at Baidu's AI lab and before that was a professor at Rutgers University. Zhang speaks quietly, usually after a careful pause. He explains that AI will be crucial to Tencent's plans to grow, especially outside China. "AI is important for the next phase," he says. "At a certain stage, you just cannot copy things. You need your own capabilities."

I ask him if Tencent might be planning some spectacular demonstrations of AI, something like AlphaGo or Lengpudashi. Tencent owns several very popular games, including the strategy title League of Legends, which is played by more than 100 million people every month. Like Go, it requires instinctive actions, and like poker, it involves playing without a clear picture of your opponents' standing. But it also requires planning far ahead, so it would be a worthy game for AI researchers to tackle next. "Right now, we have a bunch of small projects—some are more adventurous," is all Zhang will say.

Tencent's AI goals may in fact be more practical. The company has an amazing amount of conversation data thanks to WeChat and another messaging platform, called QQ. This data might be used to train machine-learning systems to hold

The headquarters of the Chinese e-commerce giant Alibaba is in Hangzhou.

more meaningful conversations. Making advances in language could have countless practical applications, from better document analysis and search to much smarter personal assistants. "The challenge, and also the opportunity, will be in natural language," Zhang says.

宏伟蓝图
THINK BIG

It might be unnerving for Western nations to see a newcomer mastering an important technology, especially when the full potential of that technology remains uncertain. But it is wrong to view this story simply in terms of competition with the West.

A big problem facing both the U.S. and China is slowing economic growth. While AI may eliminate certain jobs, it also has the potential to greatly expand the economy and create wealth by making many industries far more efficient and productive. China has embraced that simple fact more eagerly and more completely than many Western nations. But there's no reason why China's AI-fueled economic progress should come at the expense of other countries, if those countries embrace the same technology just as keenly.

China might have unparalleled resources and enormous untapped potential, but the West has world-leading expertise and a strong research culture. Rather than worry about China's progress, it would be wise for Western nations to focus on their existing strengths, investing heavily in research and education. The risk is missing out on an incredibly important technological shift. Yes, companies like Google and Facebook are making important strides in AI today, but this isn't enough to reboot a whole economy. Despite the fanfare around AI, there are few economic signs—such as increased productivity—that most of the economy is taking advantage of the technology yet. Large segments of the economy beyond Silicon Valley, like medicine, service industries, and manufacturing, also need to sign on.

I can't help thinking of the poker tournament in Hainan and reflecting that the rest of the world should take inspiration from Lengpudashi, the poker-playing AI. It's time to follow China's lead and go all in on artificial intelligence.

Will Knight is MIT Technology Review*'s senior editor covering AI.*

Don’t Let Regulators Ruin AI

Tech policy scholar Andrea O’Sullivan says the U.S. needs to be careful not to hamstring innovation.

The U.S. has so far been relatively permissive toward AI technologies—and we should keep it that way. It’s the reason so much innovation happens here rather than in the more prohibitory European nations.

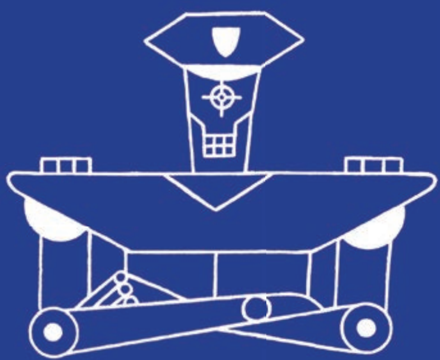
The main reason the government hasn’t hampered the industry with regulation is that there’s no overbearing federal agency dedicated strictly to AI. Instead, we have a patchwork of federal and state authorities scrutinizing these technologies. The Federal Trade Commission and the National Highway Traffic Safety Administration, for example, recently hosted a workshop to determine how to oversee automated-car technologies. The Department of Homeland Security has put out reports on potential AI threats to critical infrastructure.

The patchwork approach is imperfect, but it has one big benefit—it constrains the temptation to regulate excessively. Regulators can only apply policies that relate to their specialized knowledge.

But now a growing chorus of academics and commentators want to kill that approach. They’re calling for a whole new regulatory body to control AI technologies. Law professor Frank Pasquale of the University of Maryland has called for a “Federal Search Commission” similar to the FCC to oversee Internet queries. Attorney Matthew Scherer, in Portland, Oregon, advocates a specialized federal AI agency. Law professor Ryan Calo of the University of Washington imagines a “Federal Robotics Commission.”

Such ideas are based on the “precautionary principle”—the idea that an innovation must be decelerated or halted altogether if a regulator determines that the associated risks are too much for society to bear.

Of course, as regulatory scholars have long pointed out, the risk analyses that regulators employ can be inadequate. Imagined or exaggerated risks are weighted far more heavily than real benefits, and society is robbed of life-enriching (and in many cases life-saving) developments. Regulators often can’t resist the urge to extend their own authority or budgets, regardless of the benefits or costs to society. If you give authority to regulate, they will regulate. And once you create a federal agency, it’s incredibly difficult to make it go away.



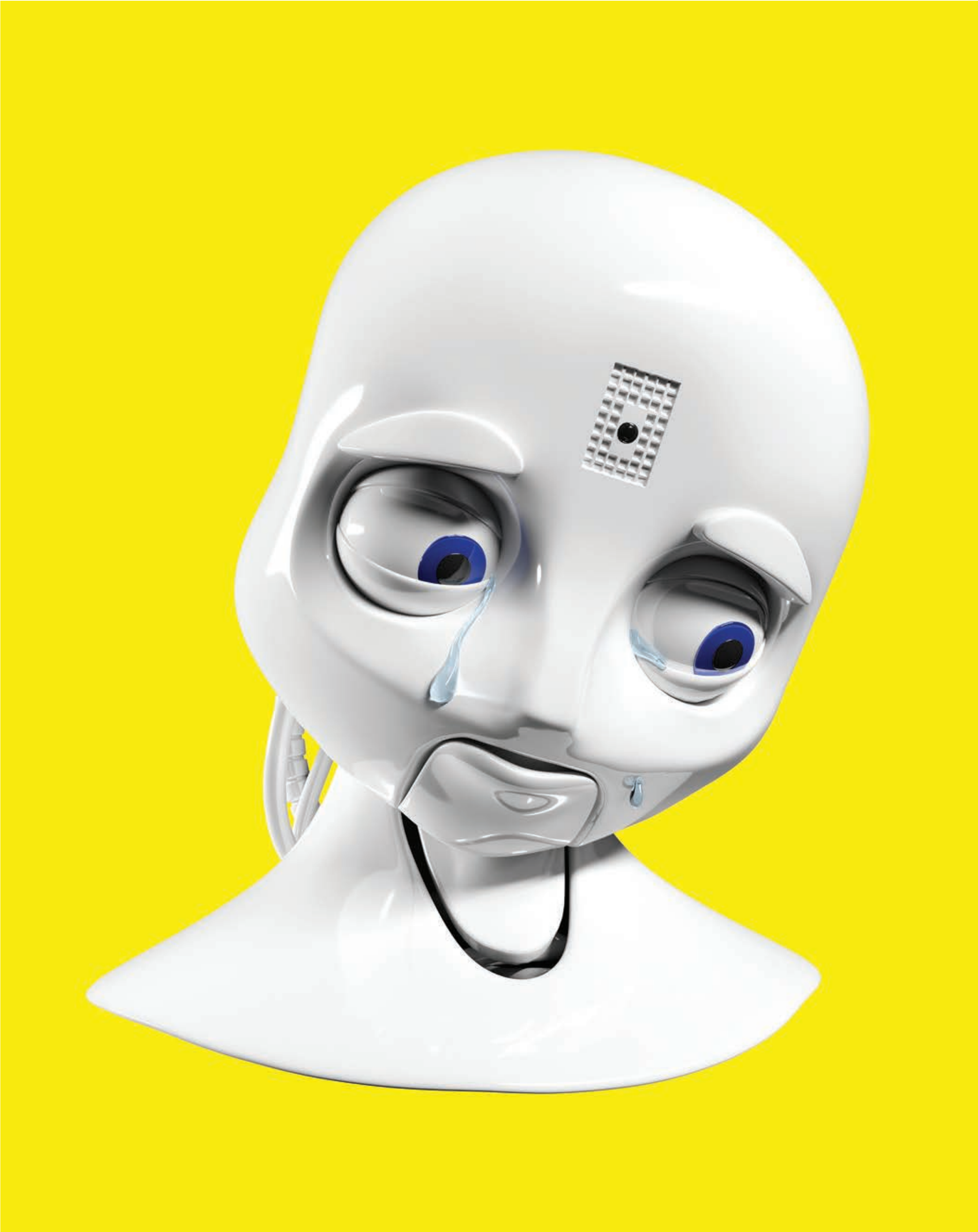
MIGUEL PORLAN

As AI grows to touch more and more domains of existence, a new federal AI agency could have a worryingly large command over American life. Policymakers would need the patience and humility to discern one AI application from another. The social risks from AI assistants, for example, are different from those posed by predictive policing software and “smart weapons.” But an overly zealous regulatory regime might erroneously lump such applications together, stifling beneficial technologies while dedicating fewer resources to the big problems that really matter.

The threat to our future and well-being that precautionary regulation poses, meanwhile, is considerable. AI technologies are poised to generate life-saving developments in health and transportation while modernizing manufacturing and trade. The projected economic benefits reach the trillions. And on a personal level, AI promises to make our lives more comfortable and simpler.

Policymakers who wish to champion growth should embrace a stance of “permissionless innovation.” Humility, collaboration, and voluntary solutions should trump the outdated “command and control” model of the last century. The age of smart machines needs a new age of smart policy.

Andrea O’Sullivan is a program manager with the Mercatus Center, a free-market-oriented think tank at George Mason University’s Technology Policy Program.



DELCAN & COMPANY + JENUE

Reviews

How We Feel About Robots That Feel

As robots become smart enough to detect our feelings and respond appropriately, they could have something like emotions of their own. But that won't necessarily make them more like humans.

By Louisa Hall

Octavia, a humanoid robot designed to fight fires on Navy ships, has mastered an impressive range of facial expressions.

When she's turned off, she looks like a human-size doll. She has a smooth white face with a snub nose. Her plastic eyebrows sit evenly on her forehead like two little capsized canoes.

When she's on, however, her eyelids fly open and she begins to display emotion. She can nod her head in a gesture of understanding; she can widen her eyes and lift both her eyebrows in a convincing semblance of alarm; or she can cock her head to one side and screw up her mouth, replicating human confusion. To comic effect, she can even arch one eyebrow and narrow the opposite eye while tapping her metal fingers together, as though plotting acts of robotic revenge.

But Octavia's range of facial expressions isn't her most impressive trait. What's amazing is that her emotional affect is an accurate response to her interactions with humans. She looks pleased, for instance, when she recognizes one of her teammates. She looks surprised when a teammate gives her a command she wasn't expecting. She looks confused if someone says something she doesn't understand.

She can show appropriate emotional affect because she processes massive amounts of information about her environment. She can see, hear, and touch. She takes visual stock of her surroundings using the two cameras built into her eyes and analyzes characteristics like facial features, complexion, and clothing. She can detect people's voices, using four microphones and a voice-recognition program called Sphinx. She can identify 25 different objects by touch, having learned them by using her fingers to physically manipulate them into various possible positions and shapes. Taken together, these perceptual skills form a part of her "embodied cognitive architecture," which allows her—according to her creators at the Navy Center for Applied Research in Artificial Intelligence—to "think and act in ways similar to people."

Culture and Human-Robot Interaction in Militarized Spaces: A War Story
By Julie Carpenter
Routledge, 2016

How Emotions Are Made: The Secret Life of the Brain
By Lisa Feldman Barrett
Houghton Mifflin Harcourt, 2017

The U.S. Army Robotic and Autonomous Systems Strategy
March 2017

That's an exciting claim, but it's not necessarily shocking. We're accustomed to the idea of machines acting like people. Automatons created in 18th-century France could dance, keep time, and play the drums, the dulcimer, or the piano. As a kid growing up in the 1980s, I for some reason coveted a doll advertised for the ability to pee in her pants.

We're even accustomed to the idea of machines thinking in ways that remind us of humans. Many of our long-cherished high-water marks for human cognition—the ability to beat a grandmaster at chess, for example, or to compose a metrically accurate sonnet—have been met and surpassed by computers.

Octavia's actions, however—the fearful widening of her eyes, the confused furrow of her plastic eyebrows—seem to go a step further. They imply that in addition to thinking the way we think, she's also feeling human emotions.

That's not really the case: Octavia's emotional affect, according to Gregory Trafton, who leads the Intelligent Systems Section at the Navy AI center, is merely meant to demonstrate the kind of thinking she's doing and make it easier for people to interact with her. But it's not always possible to draw a line between thinking and feeling. As Trafton acknowledges, "It's clear that people's thoughts and emotions are different but impact each other."

And if, as he says, "emotions influence cognition and cognition influences emotion," Octavia's ability to think, reason, and perceive points to some of the bigger questions that will accompany the rise of intelligent machines. At what point will machines be smart enough to feel *something*? And how would we really know?

Personalized feelings

Octavia is programmed with theory of mind, meaning that she can anticipate the mental states of her human teammates. She understands that people have potentially conflicting beliefs or intentions. When Octavia is given a command that differs from her expectations, she runs simulations to ascertain what the teammate who gave the command might be thinking, and why that person thinks this unexpected goal is valid. She does this by going through her own models of the world but altering them slightly, hoping to find one that leads to the stated goal. When she tilts her head to one side and furrows her eyebrows, it's to signal that she's running these simulations, trying to better understand her teammate's beliefs.

Octavia isn't programmed with emotional models. Her theory of mind is a cognitive pattern. But it functions a lot like empathy, that most cherished of all human emotions.

Other robot makers skirt the issue of their machines' emotional intelligence. SoftBank Robotics, for instance, which sells Pepper—a "pleasant and likeable" humanoid robot built to serve as a human companion—claims that Pepper can "perceive human emotion," adding that "Pepper loves to interact with you, Pepper wants to learn more about your tastes, your habits, and quite simply who you are." But though Pepper might have the ability to recognize human emotions, and though Pepper might be capable of responding with happy smiles or expressions of sadness, no one's claiming that Pepper actually *feels* such emotions.

What would it take for a robot creator to claim that? For one thing, we still don't know everything that's involved in feeling emotions.

In recent years, revolutions in psychology and neuroscience have radically redefined the very concept of emotion, making it even more difficult to pin down and describe. According to scientists such as the psychologist Lisa Feldman Barrett, a professor at Northeastern University, it is becoming increasingly clear that our emotions vary widely depending on the culture we're raised in. They even vary widely within an individual in different situations. In fact, though we share the general feelings that make up what's known as "affect" (pleasure, displeasure, arousal, and calmness) with most other humans and many other animals, our more acute and specific emotions vary more than they follow particular norms. Fear, for instance, is a culturally agreed-upon concept, but it plays out in our bodies in myriad ways. It's inspired by different stimuli, it manifests differently in our brains, and it's expressed in different ways on our faces. There's no single "fear center" or "fear circuit" in the brain, just as there's no reliably fearful facial expression: we all process and display our fear in radically different ways, depending on the situation—ways that, through interactions with other people, we learn to identify or label as "fear."

When we talk about fear, then, we're talking about a generalized umbrella concept rather than something that comes out of a specific part of the brain. As Barrett puts it, we construct emotions on the spot through an interplay of bodily systems. So how can we expect programmers to accurately model human emotion in robots?

Good soldiers

There are moral quandaries, as well, around programming robots to have emotions. These issues are especially well demonstrated by military robots that, like Octavia, are designed to be sent into frightening, painful, or potentially lethal situations in place of less dispensable human teammates.

At a 2017 conference sponsored by the Army's somewhat alarmingly titled Mad Scientist Initiative, Lieutenant General Kevin Mangum, the deputy commander for Army Training and Doctrine Command, specified that such robots should and will be autonomous. "As we look at our increasingly complex world, there's no doubt that robotics, autonomous systems, and artificial intelligence will play a role," said Mangum. The 2017 Army Robotic and Autonomous Systems Strategy predicts full integration of autonomous systems by 2040, replacing today's bomb-disposal robots and other machines that are remotely operated by humans.

When these robots can act and think on their own, should they, like Octavia, be programmed with the semblance of human emotion? Should they be programmed to actually *have* human emotion? If we're sending them into battle, should they not only think but feel alongside their human companions?

On the one hand, of course not: if we're designing robots with the express aim of exposing them to danger, it would be sadistic to give them the capacity to suffer terror, trauma, or pain.

On the other hand, however, if emotion affects intelligence and vice versa, could we be sure that a robot with no emotion would make a good soldier? What if the lack of emotion leads to stupid decisions, unnecessary risks, or excessively cruel retribution? Might a robot with no emotion decide that the intelligent decision would be to commit what a human soldier would feel was a war crime? Or would a robot with no access to fear or anger make better decisions than a human being would in the same frightening and maddening situation?

And then there's the possibility that if emotion and intelligence are inextricably linked, there's no such thing as an intelligent robot with no emotion, in which case the question of how much emotion an autonomous robot should have is, in some ways, out of the control of the programmer dealing with intelligence.

Emotional attachments

There's also the question of how these robots might affect their human teammates.

By 2010, the U.S. Army had begun deploying a fleet of about 3,000 small tactical robots, largely in response to the increasing use of improvised explosive devices in warfare. In place of human soldiers, these robots trundle down exposed roads, into dark caves, and through narrow doorways to detect and disable unpredictable IEDs.

This fleet is composed mostly of iRobot's PackBot and QinetiQ North America's Talon, robots that aren't particularly advanced. They look a little like WALL-E, their boxy metal bodies balanced on rubber treads that allow them to do a pretty good job of crossing rocky terrain, climbing stairs, and making their way down dusky hallways. They have jointed arms fitted with video cameras to survey their surroundings, and claws to tinker with explosive devices.

They're useful tools, but they're not exactly autonomous. They're operated remotely, like toy cars, by soldiers holding devices that are sometimes fitted with joysticks. As an example of AI, the PackBot isn't all that much more advanced than iRobot's better-known product, the Roomba that vacuums under your armchair.

And yet even now, despite the inexpressive nature of these robots, human soldiers develop bonds with them. Julie Carpenter demonstrates in *Culture and Human-Robot Interaction in Militarized Spaces* that these relationships are complicated, both rewarding and painful.

Even though they can't convey expressions as Octavia (top left) can, the PackBot (top right) and the Talon (below) can bring out loyalty and other kinds of emotional attachment in soldiers who work with them.

U.S. NAVAL RESEARCH LABORATORY (OCTAVIA); U.S. ARMY PHOTO BY MICHAEL J. MCLEOD (PACKBOT); QINETIQ (TALON)

When Carpenter asked one serviceman to describe his feelings about a robot that had been destroyed, he responded:

> I mean, it wasn't obviously ... anywhere close to being on the same level as, like, you know, a buddy of yours getting wounded or seeing a member getting taken out or something like that. But there was still a certain loss, a sense of loss from something happening to one of your robots.

Another serviceman compared his robot to a pet dog:

> I mean, you took care of that thing as well as you did your team members. And you made sure it was cleaned up, and made sure the batteries were always charged. And if you were not using it, it was tucked safely away as best could be because you knew if something happened to the robot, well then, it was your turn, and nobody likes to think that.

Yet another man explained why his teammate gave their robot a human name:

> Towards the end of our tour we were spending more time outside the wire sleeping in our trucks than we were inside. We'd sleep inside our trucks outside the wire for a good five to six days out of the week, and it was three men in the truck, you know, one laid across the front seats; the other lays across the turret. And we can't download sensitive items and leave them outside the truck. Everything has to be locked up, so our TALON was in the center aisle of our truck and our junior guy named it Danielle so he'd have a woman to cuddle with at night.

These men all stress that the robots are tools, not living creatures with feelings. Still, they give their robots human names and tuck them in safely at night. They joke about that impulse, but there's a slightly disturbing dissonance in the jokes. The servicemen Carpenter interviewed seem to feel somewhat stuck between two feelings: they understand the absurdity of caring for an emotionless robot that is designed to be expendable, but they nevertheless experience the temptation to care, at least a little bit.

Once Carpenter had published her initial interviews, she received more communication from men and women in the military who had developed real bonds with their robots. One former explosive ordnance disposal technician wrote:

> As I am an EOD technician of eight years and three deployments, I can tell you that I found your research extremely interesting. I can completely agree with the other techs you interviewed in saying that the robots are tools and as such I will send them into any situation regardless of the possible danger.
>
> However, during a mission in Iraq in 2006, I lost a robot that I had named "Stacy 4" (after my wife who is an EOD tech as well). She was an excellent robot that never gave me any issues, always performing flawlessly. Stacy 4 was completely destroyed and I was only able to recover very small pieces of the chassis. Immediately following the blast that destroyed Stacy 4, I can still remember the feeling of anger, and lots of it. "My beautiful robot was killed ..." was actually the statement I made to my team leader. After the mission was complete and I had recovered as much of the robot as I could, I cried at the loss of her. I felt as if I had lost a dear family member. I called my wife that night and told her about it too. I know it sounds dumb but I still hate thinking about it. I know that the robots we use are just machines and I would make the same decisions again, even knowing the outcome.
>
> I value human life. I value the relationships I have with real people. But I can tell you that I sure do miss Stacy 4, she was a good robot.

If these are the kinds of testimonials that can be gathered from soldiers interacting with faceless machines like PackBots and Talons, what would you hear from soldiers deployed with robots like Octavia, who see and hear and touch and can anticipate her human teammates' states of mind?

In popular conversations about the ethics of giving feelings to robots, we tend to focus on the effects of such technological innovation on the robots themselves. Movies and TV shows from *Blade Runner* to *Westworld* attend to the trauma that would be inflicted on feeling robots by humans using them for their entertainment. But there is also the inverse to consider: the trauma inflicted on the humans who bond with robots and then send them to certain deaths.

What complicates all this even further is that if a robot like Octavia ends up feeling human emotions, those feelings won't only be the result of the cognitive architecture she's given to start with. If they're anything like our emotions, they'll evolve in the context of her relationships with her teammates, her place in the world she inhabits.

If her unique robot life, for instance, is spent getting sent into fires by her human companions, or trundling off alone down desert roads laced with explosive devices, her emotions will be different from those experienced by a more sheltered robot, or a more sheltered human. Regardless of the recognizable emotional expressions she makes, if she spends her life in inhumane situations, her emotions might not be recognizably human.

Louisa Hall, a writer in New York, is the author of Speak, *a 2015 novel about artificial intelligence.*

The Seven Deadly Sins of AI Predictions

Mistaken extrapolations, limited imagination, and other common mistakes that distract us from thinking more productively about the future.

By Rodney Brooks

We are surrounded by hysteria about the future of artificial intelligence and robotics—hysteria about how powerful they will become, how quickly, and what they will do to jobs.

I recently saw a story in MarketWatch that said robots will take half of today's jobs in 10 to 20 years. It even had a graphic to prove the numbers.

The claims are ludicrous. (I try to maintain professional language, but sometimes …) For instance, the story appears to say that we will go from one million grounds and maintenance workers in the U.S. to only 50,000 in 10 to 20 years, because robots will take over those jobs. How many robots are currently operational in those jobs? *Zero*. How many realistic demonstrations have there been of robots working in this arena? *Zero*. Similar stories apply to all the other categories where it is suggested that we will see the end of more than 90 percent of jobs that currently require physical presence at some particular site.

Mistaken predictions lead to fears of things that are not going to happen, whether it's the wide-scale destruction of jobs, the Singularity, or the advent of AI that has values different from ours and might try to destroy us. We need to push back on these mistakes. But why are people making them? I see seven common reasons.

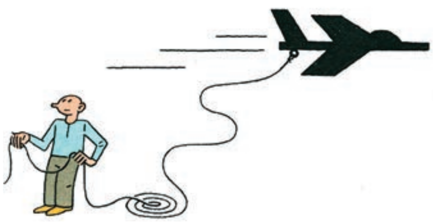
1. Overestimating and underestimating

Roy Amara was a cofounder of the Institute for the Future, in Palo Alto, the intellectual heart of Silicon Valley. He is best known for his adage now referred to as Amara's Law:

> We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run.

There is a lot wrapped up in these 21 words. An optimist can read it one way, and a pessimist can read it another.

A great example of the two sides of Amara's Law is the U.S. Global Positioning System. Starting in 1978, a constellation of 24 satellites (now 31 including spares) were placed in orbit. The goal of GPS was to allow precise delivery of munitions by the U.S. military. But the program was nearly canceled again and again in the 1980s. The first operational use for its intended purpose was in 1991 during Desert Storm; it took several more successes for the military to accept its utility.



JOOST SWARTE

Today GPS is in what Amara would call the long term, and the ways it is used were unimagined at first. My Series 2 Apple Watch uses GPS while I am out running, recording my location accurately enough to see which side of the street I run along. The tiny size and price of the receiver would have been incomprehensible to the early GPS engineers. The technology synchronizes physics experiments across the globe and plays an intimate role in synchronizing the U.S. electrical grid and keeping it running. It even allows the high-frequency traders who really control the stock market to mostly avoid disastrous timing errors. It is used by all our airplanes, large and small, to navigate, and it is used to track people out of prison on parole. It determines which seed variant will be planted in which part of many fields across the globe. It tracks fleets of trucks and reports on driver performance.

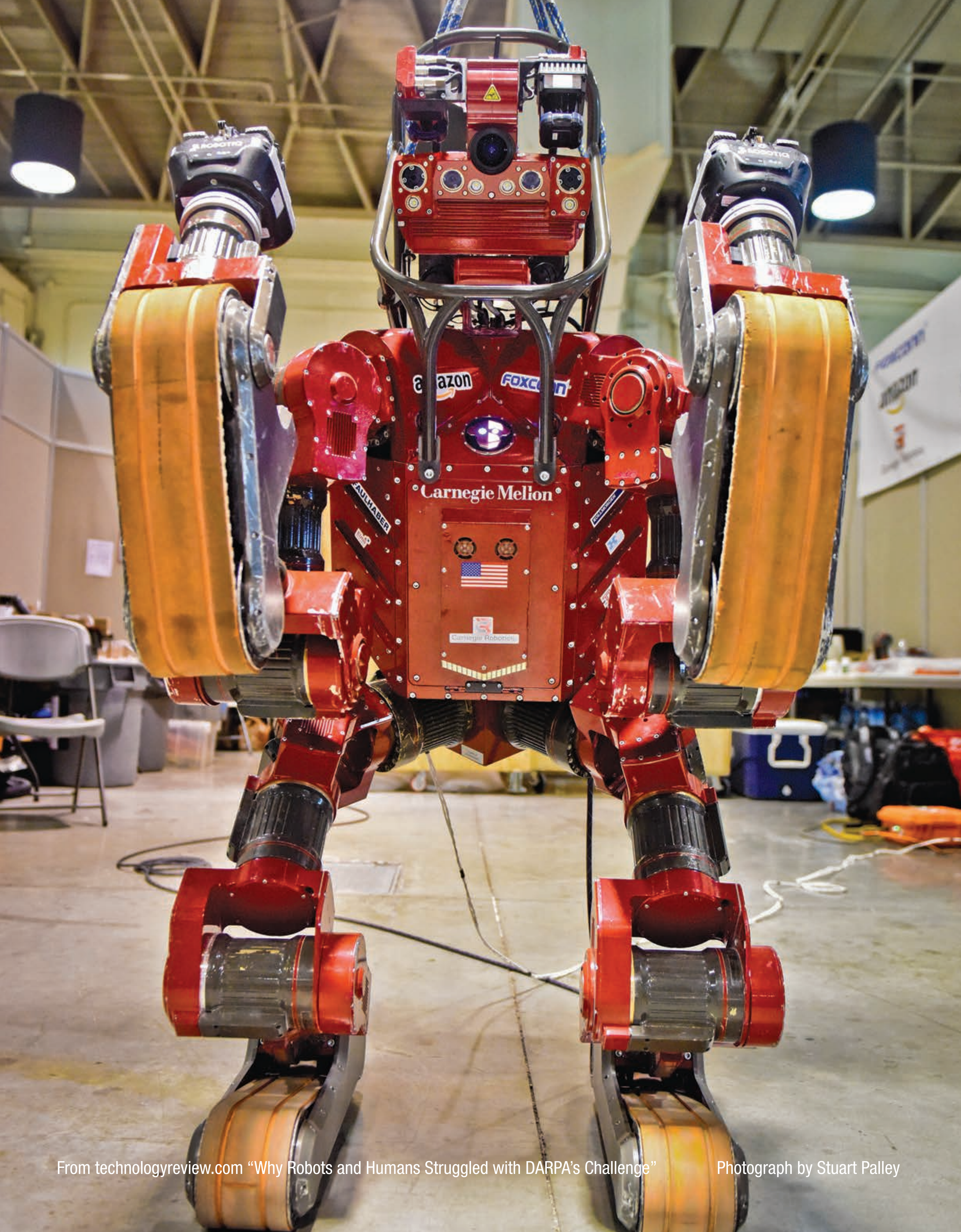
GPS started out with one goal, but it was a hard slog to get it working as well as was originally expected. Now it has seeped into so many aspects of our lives that we would not just be lost if it went away; we would be cold, hungry, and quite possibly dead.

We see a similar pattern with other technologies over the last 30 years. A big promise up front, disappointment, and then slowly growing confidence in results that exceed the original expectations. This is true of computation, genome sequencing, solar power, wind power, and even home delivery of groceries.

AI has been overestimated again and again, in the 1960s, in the 1980s, and I believe again now, but its prospects for the long term are also probably being underestimated. The question is: *How long is the long term*? The next six errors help explain why the time scale is being grossly underestimated for the future of AI.

2. Imagining magic

When I was a teenager, Arthur C. Clarke was one of the "big three" science fiction writers, along with Robert Heinlein and Isaac Asimov. But Clarke was also an inventor, a science writer, and a futurist. Between 1962 and 1973 he formulated



From technologyreview.com "Why Robots and Humans Struggled with DARPA's Challenge" Photograph by Stuart Palley

three adages that have come to be known as Clarke's Three Laws:

> When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.
>
> The only way of discovering the limits of the possible is to venture a little way past them into the impossible.
>
> Any sufficiently advanced technology is indistinguishable from magic.

Personally, I should probably be wary of the second sentence in his first law, as I am much more conservative than some others about how quickly AI will be ascendant. But for now I want to expound on Clarke's Third Law.

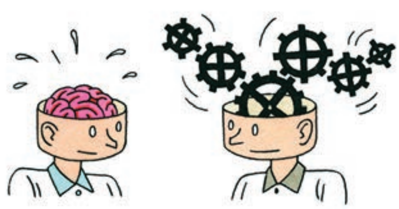
Imagine we had a time machine and we could transport Isaac Newton from the late 17th century to today, setting him down in a place that would be familiar to him: Trinity College Chapel at the University of Cambridge.

Now show Newton an Apple. Pull out an iPhone from your pocket, and turn it on so that the screen is glowing and full of icons, and hand it to him. Newton, who revealed how white light is made from components of different-colored light by pulling apart sunlight with a prism and then putting it back together, would no doubt be surprised at such a small object producing such vivid colors in the darkness of the chapel. Now play a movie of an English country scene, and then some church music that he would have heard. And then show him a Web page with the 500-plus pages of his personally annotated copy of his masterpiece *Principia*, teaching him how to use the pinch gesture to zoom in on details.

Could Newton begin to explain how this small device did all that? Although he invented calculus and explained both optics and gravity, he was never able to sort out chemistry from alchemy. So I think he would be flummoxed, and unable to come up with even the barest coherent outline of what this device was. It would be no different to him from an embodiment of the occult—something that was of great interest to him. It would be indistinguishable from magic. And remember, Newton was a really smart dude.

If something is magic, it is hard to know its limitations. Suppose we further show Newton how the device can illuminate the dark, how it can take photos and movies and record sound, how it can be used as a magnifying glass and as a mirror. Then we show him how it can be used to carry out arithmetical computations at incredible speed and to many decimal places. We show it counting the steps he has taken as he carries it, and show him that he can use it to talk to people anywhere in the world, immediately, from right there in the chapel.

What else might Newton conjecture that the device could do? Prisms work forever. Would he conjecture that the iPhone would work forever just as it is, neglecting to understand that it needs to be recharged? Recall that we nabbed him from a time 100 years before the birth of



Michael Faraday, so he lacked a scientific understanding of electricity. If the iPhone can be a source of light without fire, could it perhaps also transmute lead into gold?

This is a problem we all have with imagined future technology. If it is far enough away from the technology we have and understand today, then we do not know its limitations. And if it becomes indistinguishable from magic, anything one says about it is no longer falsifiable.

This is a problem I regularly encounter when trying to debate with people about whether we should fear artificial general intelligence, or AGI—the idea that we will build autonomous agents that operate much like beings in the world. I am told that I do not understand how powerful AGI will be. That is not an argument. We have no idea whether it can even exist. I would like it to exist—this has always been my own motivation for working in robotics and AI. But modern-day AGI research is not doing well at all on either being general or supporting an independent entity with an ongoing existence. It mostly seems stuck on the same issues in reasoning and common sense that AI has had problems with for at least 50 years. All the evidence that I see says we have no real idea yet how to build one. Its properties are completely unknown, so rhetorically it quickly becomes magical, powerful without limit.

Nothing in the universe is without limit.

Watch out for arguments about future technology that is magical. Such an argument can never be refuted. It is a faith-based argument, not a scientific argument.

3. Performance versus competence

We all use cues about how people perform some particular task to estimate how well they might perform some different task. In a foreign city we ask a stranger on the street for directions, and she replies with confidence and with directions that seem to make sense, so we figure we can also ask her about the local system for paying when you want to take a bus.

Now suppose a person tells us that a particular photo shows people playing Frisbee in the park. We naturally assume that this person can answer questions like *What is the shape of a Frisbee? Roughly* *how far can a person throw a Frisbee? Can a person eat a Frisbee? Roughly how many people play Frisbee at once? Can a three-month-old person play Frisbee? Is today's weather suitable for playing Frisbee?*

Computers that can label images like "people playing Frisbee in a park" have no chance of answering those questions. Besides the fact that they can only label more images and cannot answer ques-

tions at all, they have no idea what a person is, that parks are usually outside, that people have ages, that weather is anything more than how it makes a photo look, etc.

This does not mean that these systems are useless; they are of great value to search engines. But here is what goes wrong. People hear that some robot or some AI system has performed some task. They then generalize from that performance to a competence that a person performing the same task could be expected to have. And they apply that generalization to the robot or AI system.

Today's robots and AI systems are incredibly narrow in what they can do. Human-style generalizations do not apply.

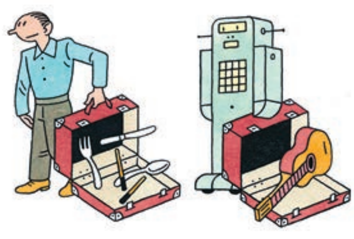
4. Suitcase words

Marvin Minsky called words that carry a variety of meanings "suitcase words." "Learning" is a powerful suitcase word; it can refer to so many different types of experience. Learning to use chopsticks is a very different experience from learning the tune of a new song. And learning to write code is a very different experience from learning your way around a city.

When people hear that machine learning is making great strides in some new domain, they tend to use as a mental model the way in which a person would learn that new domain. However, machine learning is very brittle, and it requires lots of preparation by human researchers or engineers, special-purpose coding, special-purpose sets of training data, and a custom learning structure for each new problem domain. Today's machine learning is not at all the sponge-like learning that humans engage in, making rapid progress in a new domain without having to be surgically altered or purpose-built.

Likewise, when people hear that a computer can beat the world chess champion (in 1997) or one of the world's best Go players (in 2016), they tend to think that it is "playing" the game just as a human would. Of course, in reality those programs had no idea what a game actually was, or even that they were playing. They were also much less adaptable. When humans play a game, a small change in rules does not throw them off. Not so for AlphaGo or Deep Blue.

Suitcase words mislead people about how well machines are doing at tasks that people can do. That is partly because AI researchers—and, worse, their institutional press offices—are eager to claim progress in an instance of a suitcase



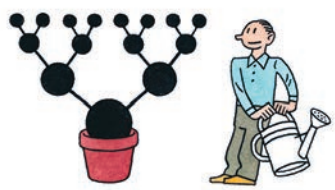
concept. The important phrase here is "an instance." That detail soon gets lost. Headlines trumpet the suitcase word, and warp the general understanding of where AI is and how close it is to accomplishing more.

5. Exponentials

Many people are suffering from a severe case of "exponentialism."

Everyone has some idea about Moore's Law, which suggests that computers get better and better on a clockwork-like schedule. What Gordon Moore actually said was that the number of components that could fit on a microchip would double every year. That held true for 50 years, although the time constant for doubling gradually lengthened from one year to over two years, and the pattern is coming to an end.

Doubling the components on a chip has made computers continually double in speed. And it has led to memory



chips that quadruple in capacity every two years. It has also led to digital cameras that have better and better resolution, and LCD screens with exponentially more pixels.

The reason Moore's Law worked is that it applied to a digital abstraction of a true-or-false question. In any given circuit, is there an electrical charge or voltage there or not? The answer remains clear as chip components get smaller and smaller—until a physical limit intervenes, and we get down to components with so few electrons that quantum effects start to dominate. That is where we are now with our silicon-based chip technology.

When people are suffering from exponentialism, they may think that the exponentials they use to justify an argument are going to continue apace. But Moore's Law and other seemingly exponential laws can fail because they were not truly exponential in the first place.

Back in the first part of this century, when I was running MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) and needed to help raise money for over 90 different research groups, I tried to use the memory increase on iPods to show sponsors how things were continuing to change very rapidly. Here are the data on how much music storage one got in an iPod for $400 or less:

year	gigabytes
2002	10
2003	20
2004	40
2006	80
2007	160

Then I would extrapolate a few years out and ask what we would do with all that memory in our pockets.

Extrapolating through to today, we would expect a $400 iPod to have 160,000 gigabytes of memory. But the top iPhone of today (which costs much more than $400) has only 256 gigabytes of memory, less than double the capacity of the 2007 iPod. This particular exponential collapsed very suddenly once the amount of memory got to the point where it was big enough to hold any reasonable person's music library and apps, photos, and videos. Exponentials can collapse when a physical limit is hit, or when there is no more economic rationale to continue them.

Similarly, we have seen a sudden increase in performance of AI systems thanks to the success of deep learning. Many people seem to think that means we will continue to see AI performance increase by equal multiples on a regular basis. But the deep-learning success was 30 years in the making, and it was an isolated event.

That does not mean there will not be more isolated events, where work from the backwaters of AI research suddenly fuels a rapid-step increase in the performance of many AI applications. But there is no "law" that says how often they will happen.

6. Hollywood scenarios

The plot for many Hollywood science fiction movies is that the world is just as it is today, except for one new twist.

In *Bicentennial Man*, Richard Martin, played by Sam Neill, sits down to breakfast and is waited upon by a walking, talking humanoid robot, played by Robin Williams. Richard picks up a newspaper to read over breakfast. A newspaper! Printed on paper. Not a tablet computer, not a podcast coming from an Amazon Echo–like device, not a direct neural connection to the Internet.

It turns out that many AI researchers and AI pundits, especially those pessimists who indulge in predictions about AI getting out of control and killing people, are similarly imagination-challenged. They ignore the fact that if we are able to eventually build such smart devices, the world will have changed significantly by then. We will not suddenly be surprised by the existence of such super-intelligences. They

will evolve technologically over time, and our world will come to be populated by many other intelligences, and we will have lots of experience already. Long before there are evil super-intelligences that want to get rid of us, there will be somewhat less intelligent, less belligerent machines. Before that, there will be really grumpy machines. Before that, quite annoying machines. And before them, arrogant, unpleasant machines. We will change our world along the way, adjusting both the environment for new technologies and the new technologies themselves. I am not saying there may not be challenges. I am saying that they will not be sudden and unexpected, as many people think.

7. Speed of deployment

New versions of software are deployed very frequently in some industries. New features for platforms like Facebook are deployed almost hourly. For many new features, as long as they have passed integration testing, there is very little economic downside if a problem shows up in the field and the version needs to be pulled back. This is a tempo that Silicon Valley and Web software developers have gotten used to. It works because the marginal cost of newly deploying code is very, very close to zero.

Deploying new hardware, on the other hand, has significant marginal costs. We know that from our own lives. Many of the cars we are buying today, which are not self-driving, and mostly are not software-enabled, will probably still be on the road in the year 2040. This puts an inherent limit on how soon all our cars will be self-driving. If we build a new home today, we can expect that it might be around for over 100 years. The building I live in was built in 1904, and it is not nearly the oldest in my neighborhood.

Capital costs keep physical hardware around for a long time, even when there are high-tech aspects to it, and even when it has an existential mission.

The U.S. Air Force still flies the B-52H variant of the B-52 bomber. This version was introduced in 1961, making it 56 years old. The last one was built in 1962, a mere 55 years ago. Currently these planes are expected to keep flying until at least 2040, and perhaps longer—there is talk of extending their life to 100 years.

I regularly see decades-old equipment in factories around the world. I even see

Talent Is Global; Trading Can Be Taught

by MIT Technology Review Custom
in partnership with WorldQuant, LLC

WorldQuant® is a quantitative investment firm with a global perspective, so it makes sense that the Connecticut-based company would draw on talent both near and far.

In fact, talent development has been the backbone of WorldQuant since its founding in 2007. The company's team of researchers, portfolio managers, and technologists now includes more than 450 professionals in 18 offices worldwide, reflecting its core belief that talent is global.

As WorldQuant grows, the company retains that global emphasis—both in its search for talent and in its support of philanthropic and academic endeavors. "We saw a great need to provide a free, accessible simulation platform," says Jeffrey Scott, director of WorldQuant's Virtual Research Center. "Tremendous things can happen when you open the door to people from all backgrounds and locations."

To that end, WorldQuant has created a proprietary modeling platform for those who want to pursue their interest in the area of financial trading models. Anyone interested in exploring this field can take part in the WorldQuant Challenge, an ongoing, worldwide competition for building "alphas"—mathematical models. Participants try to create high-performing algorithms for stock-price movement prediction and then vie for incentives such as an invitation to join WorldQuant's Research Consultant program. The program provides a part-time, "learn and earn" consulting opportunity to qualified individuals and has proven very popular with numerous university students.

Some 30,000 people worldwide have taken part in the WorldQuant Challenge during the past three years. While the algorithmic work hinges on an understanding of mathematics, there's no definitive academic background for a quantitative researcher, or "quant," Scott says. "If I were to poll a dozen Research Consultants, I might find a dozen different majors reflected. And they encompass every STEM major—including all engineering disciplines, all math disciplines, the various sciences, technology including computer science, along with finance, economics, and business. So it's a very wide net that's cast."

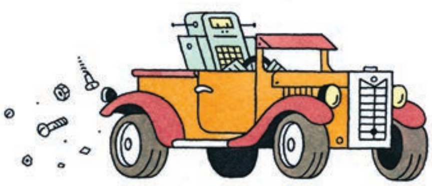
The year-round WorldQuant Challenge spawned a spinoff for American students: the Solve-a-thon at MIT, hosted by the MIT-based Solve program and MIT Technology Review over a two-month period, culminating in January 2016. Sponsored by WorldQuant, the Solve-a-thon at MIT attracted more than 700 contestants from 140-plus universities and colleges, who took part in training sessions to learn about finance and alphas, and then sought to build predictive models. Using WorldQuant's WebSim platform, a Web-based financial market simulation tool, participants created their own alphas to try to predict future movements in the stock market. Throughout the competition, they amassed points for generating high-performing alphas, and the highest scorers earned cash prizes from MIT.

The overall winner was Song Wang, a financial engineering student at Baruch College in New York City. He scored more than 100,000 points, almost double the number of his closest competitor, by working "hard and smart," says Scott. "He was creative in building unique ideas, and tried to build on previous success as well as looking into new areas of opportunity and new data elements. He was persistent and very creative with his ideas"—all qualities that are important in the world of quantitative finance.

WorldQuant plans to sponsor a second Solve-a-thon at MIT in September 2016. In addition, highly competitive global competitions with potential financial incentives also take place throughout the year, including seasonal "Alphathons." Meanwhile, to learn more about creating alphas and training for a career as a "quant," sign up any time at www.WorldQuantChallenge.com to take the WorldQuant Challenge.

PCs running Windows 3.0—a software version released in 1990. The thinking is "If it ain't broke, don't fix it." Those PCs and their software have been running the same application doing the same task reliably for over two decades.

The principal control mechanism in factories, including brand-new ones in the U.S., Europe, Japan, Korea, and China, is based on programmable logic controllers, or PLCs. These were introduced in 1968 to replace electromechanical relays. The "coil" is still the principal abstraction unit used today, and PLCs are programmed as though they were a network of 24-volt electromechanical relays. Still. Some of the direct wires have been replaced by Ethernet cables. But they are not part of an open network. Instead they are individual cables, run point to point, physically embodying the control flow—the order in which steps get executed—in these brand-new ancient automation controllers. When you want to change information flow, or control flow, in most factories around the world, it takes weeks of consultants figuring out what is there,



designing new reconfigurations, and then teams of tradespeople to rewire and reconfigure hardware. One of the major manufacturers of this equipment recently told me that they aim for three software upgrades every 20 years.

In principle, it could be done differently. In practice, it is not. I just looked on a jobs list, and even today, this very day, Tesla Motors is trying to hire PLC technicians at its factory in Fremont, California. They will use electromagnetic relay emulation in the production of the most AI-enhanced automobile that exists.

A lot of AI researchers and pundits imagine that the world is already digital, and that simply introducing new AI systems will immediately trickle down to operational changes in the field, in the supply chain, on the factory floor, in the design of products.

Nothing could be further from the truth. Almost all innovations in robotics and AI take far, far, longer to be really widely deployed than people in the field and outside the field imagine.

Rodney Brooks is a former director of the Computer Science and Artificial Intelligence Laboratory at MIT and a founder of Rethink Robotics and iRobot. This essay is adapted with permission from a post that originally appeared at rodneybrooks.com.

Statement of Ownership, Management and Circulation. (Required by U.S.C. 3685.) (1). Publication Title: MIT Technology Review, (2). Publication No. 535-940, (3). Filing Date: 9/13/2017, (4). Issue Frequency: Bi-monthly. (5). No. of Issues Published Annually: 6. (6) Annual Subscription Price: $29.95 (7). Complete Mailing Address of Known Office of Publication: One Main St, 13th Floor, Cambridge, MA 02142 (8). Complete Mailing Address of Headquarters or General Business Office of Publisher: One Main St, 13th Floor, Cambridge, MA 02142 (9). Full Names and Complete Mailing Addresses of Publisher, Editor, and Managing Editor. Publisher: Elizabeth Bramson-Boudreau, One Main St, 13th Floor, Cambridge, MA 02142. Editor: David Rotman, One Main St, 13th Floor, Cambridge, MA 02142. Managing Editor: Timothy Maher, One Main St, 13th Floor, Cambridge, MA 02142. (10). Owner: Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02138. (11). Known Bondholders, Mortgagees, and Other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, or other Securities: None. (12). Tax Status: The purpose, function, and nonprofit status of this organization and the exempt status for federal income tax purposes: Has Not Changed During Preceding 12 months. (13). Publication Title: MIT Technology Review. (14) Issue Date for Circulation Data Below: July/August 2017. (15). Extent and Nature of Circulation: (a) Total No. of Copies (Net Press Run): Average No. Copies Each Issue During Preceding 12 Months: 210,897; No. Copies of Single Issue Published Nearest to Filing Date: 218,208. (b) Legitimate Paid and/or Requested Distribution (1) Mailed Outside-County Paid Subscriptions Stated on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 164,758, No. Copies of Single Issue Published Nearest to Filing Date: 169,082. (2) In-County Paid/Requested Mail Subscriptions Stated on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (3) Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Paid Distribution Outside the USPS: Average No. Copies Each Issue During Preceding 12 Months: 11,856, No. Copies of Single Issue Published Nearest to Filing Date: 11,537. (4) Paid Distribution by Other Mail Classes Through the USPS: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (c) Total Paid and/or Requested Distribution: Average No. Copies Each Issue During Preceding 12 Months: 176,623, No. Copies of Single Issue Published Nearest to Filing Date: 180,619. (d) Nonrequested Distribution: (1) Outside-County Nonrequested Copies included on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 573, No. Copies of Single Issue Published Nearest to Filing Date: 763. (2) In-County Nonrequested Copies included on PS Form 3541: Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0. (3) Nonrequested Copies Distributed Through the USPS by Other Classes of Mail: 0 Average No. Copies Each Issue During Preceding 12 Months: 0, No. Copies of Single Issue Published Nearest to Filing Date: 0 (4) Nonrequested Copies Distributed Outside the Mail: Average No. Copies Each Issue During Preceding 12 Months: 4,581, No. Copies of Single Issue Published Nearest to Filing Date: 6764. (e) Total Free or Nominal Rate Distribution: Average No. Copies Each Issue During Preceding 12 Months: 5,154, No. Copies of Single Issue Published Nearest to Filing Date: 7527. (f) Total Distribution: Average No. Copies Each Issue During Preceding 12 Months: 181,777, No. Copies of Single Issue Published Nearest to Filing Date: 188146. (g) Copies not Distributed: Average No. Copies Each Issue During Preceding 12 Months: 29,120, No. Copies of Single Issue Published Nearest to Filing Date: 30,062. (h) Total: Average No. Copies Each Issue During Preceding 12 Months: 210,897, No. Copies of Single Issue Published Nearest to Filing Date: 218,208. (i) Percent Paid: Average No. Copies Each Issue During Preceding 12 Months: 97.2%, No. Copies of Single Issue Published Nearest to Filing Date: 96.0%. This Statement of Ownership will be printed in the November/December issue of this publication. I certify that all the information furnished on this form is true and complete. Electronic Copy Circulation: Requested and Paid Electronic Copies: Average No. Copies Each Issue During Preceding 12 Months: 14,989 No. Copies of Single Issue Published Nearest to Filing Date: 15,039 Total requested and paid copies: Average No. Copies Each Issue During Preceding 12 Months: 176,623 No. Copies of Single Issue Published Nearest to Filing Date: 180,619. Total Requested Copy Distribution (Line 15F) + Requested Paid Electronic Copies: Average No. Copies Each Issue During Preceding 12 Months: 181,776 No. Copies of Single Issue Published Nearest to Filing Date: 188,146. Percent Paid and /or Reqested (16B divided by 16c x 100): Average No. Copies Each Issue During Preceding 12 Months: 97.2% No. Copies of Single Issue Published Nearest to Filing Date: 96% **Doreen Adger, SVP of Consumer Revenues and Marketing.**

Trevor Paglen
A Man (Corpus: The Humans)
from the series
Adversarially Evolved Hallucination
2017

What do machine hallucinations look like? Trevor Paglen, who has been an artist in residence at Stanford, unearths them by training facial-recognition systems on particular sets of images. This picture is one that a computer recognized as a man after Paglen fed it images associated with omens, portents, monsters, and dreams. Sure, giving the machine *those* training images is a bit of a trick, but Paglen's point is that any data fed to AI is chosen subjectively. Computers do not see the world precisely as it is; they see it within the limits of the data given to them to represent the world. That's a flaw AI and people have in common.

MIT Technology Review (ISSN 1099-274X), November/December 2017 issue, Reg. U.S. Patent Office, is published bimonthly by MIT Technology Review, 1 Main St. Suite 13, Cambridge, MA 02142-1517. Entire contents ©2017. The editors seek diverse views, and authors' opinions do not represent the official policies of their institutions or those of MIT. Periodicals postage paid at Boston, MA, and additional mailing offices. Postmaster: send address changes to MIT Technology Review, Subscriber Services, PO Box 5001, Big Sandy, TX 75755, or via the Internet at www.technologyreview.com/customerservice. Basic subscription rates: $41.94 per year within the United States; in all other countries, US$54. Publication Mail Agreement Number 40621028. Send undeliverable Canadian copies to PO Box 1051 Fort Erie, ON L2A 6C7. Printed in U.S.A. Audited by the Alliance for Audited Media


FIFTH THIRD BANK
YOUR FUTURE GROWTH CAPITAL BEGINS WITH FIFTH THIRD BANK
Fifth Third Commercial Banking connects you with a network of industry experts to provide tailored advice and power your business forward.
This is Banking a Fifth Third Better℠.
53.com/Future
MEMBER FDIC