QUANTUM PHYSICS
How Reality Gets Created

EVOLUTION
Origins of Life's Complexity

HEALTH
Why Exercise Works Wonders

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AUGUST 2013

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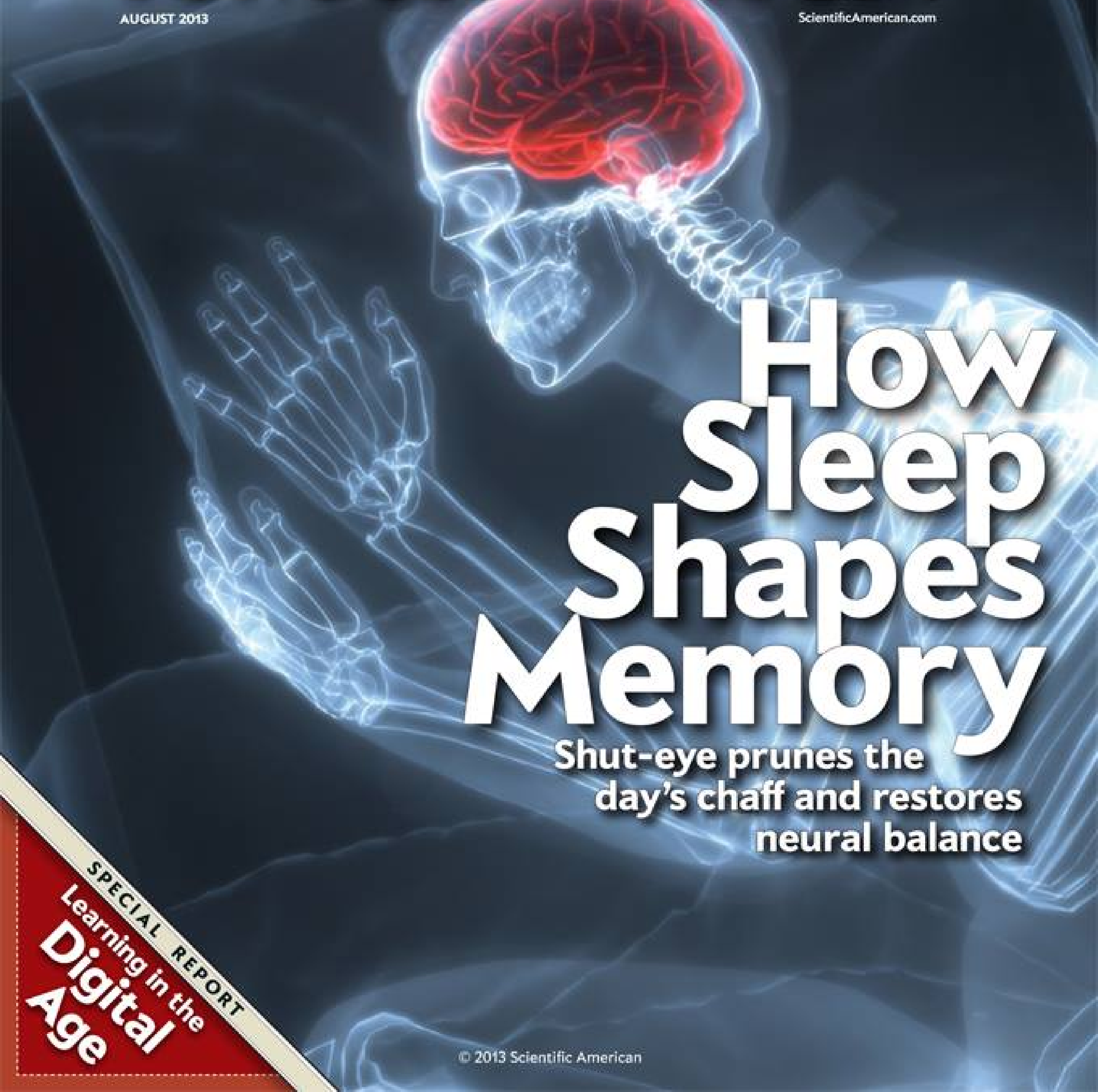


How Sleep Shapes Memory

Shut-eye prunes the day's chaff and restores neural balance

SPECIAL REPORT
Learning in the Digital Age

SCIENTIFIC AMERICAN

August 2013 Volume 309, Number 2

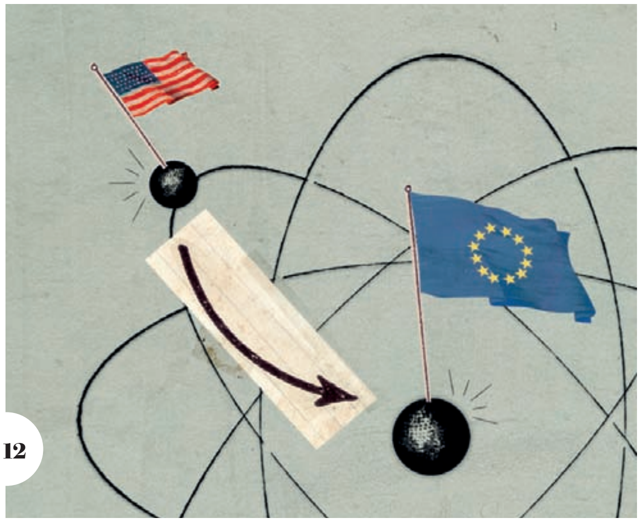
ON THE COVER

Sleep has long been thought to strengthen the synapses linking nerve cells in the brain, thus helping to cement memories of the day. An alternative view holds that many newly formed synapses weaken during sleep and that we should be glad they do.

Image by Mirko Ilić.

FEATURES

GETTY IMAGES



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21

96

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DEPARTMENTS

ON THE WEB

Meet the Future of Science
In July 625 young scientists from 78 countries and 35 Nobel Prize winners convened at the 63rd Lindau Nobel Laureate Meeting in Germany. We highlight 30 extraordinary researchers under the age of 30 in our special coverage of the meeting. *Go to www.ScientificAmerican.com/aug2013/lindau*

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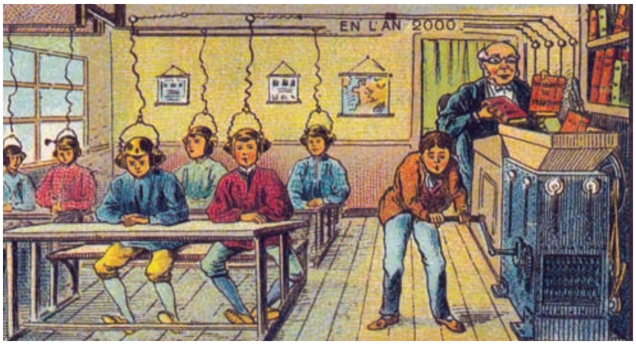
Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina



Bits for Brains

IN THIS POSTCARD FROM A SERIES BEGINNING IN THE LATE 19TH century, Jean-Marc Côté, a French artist, depicts a classroom in the year 2000. Rather than lecturing, the instructor drops texts into a hand-cranked device that delivers information straight to the pupils' ears.

A century later our perspective on where learning is headed is obviously different but perhaps no less remarkable to us. That future is also closer than ever: just as digital technology has led to transformations in many areas of our lives—from instantly finding information online to harnessing big data for managing society's needs—it is now sweeping through education.

We face a confluence of changes. Because basic research is increasingly recognized as the engine of innovation and prosperity, the U.S. and others are placing a greater emphasis on science, technology, engineering and math (STEM). Those efforts require shifts in policy (such as the new Next Generation Science Standards) and in teaching (an initiative of the Obama administration seeks to add 100,000 STEM teachers in the next decade), as well as public-private collaborations, such as *Scientific American*'s own initiatives with the nonprofit Change the Equation (part of the administration's Educate to Innovate program).

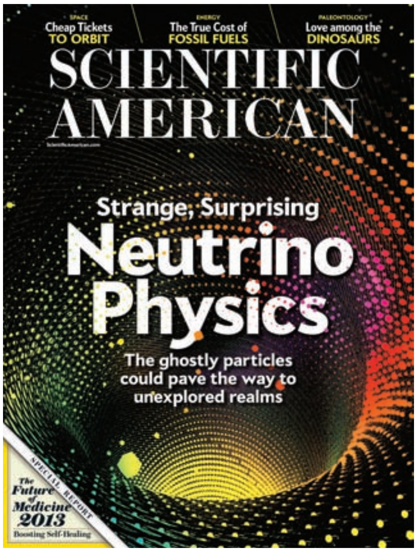
At the same time, classroom opportunities are not uniformly distributed, and quality can be uneven. Broadband transmission of instruction, combined with the kind of adaptive techniques that allow shopping sites to learn what you prefer, promise to offer access on a scale never before possible. Downsides include possibly hindering teachers' mentoring role—traditionally built through direct interaction—and privacy and efficacy concerns.

For all these reasons, we decided to create this issue's special report, "Learning in the Digital Age." In the section, award-winning foreign correspondent Jeffrey Bartholet takes a close look at using massive open online courses (MOOCs) to broaden access to education in "Hype and Hope," starting on page 53. In "Machine Learning," on page 62, senior editor Seth Fletcher delves into the promise of adaptive learning, in which software tailors the questions and lessons based on a student's performance. Rounding out the report are essays from experts who provide unique viewpoints, such as U.S. Secretary of Education Arne Duncan. On page 73, we end with the results of a student poll about participants' experiences with MOOCs, conducted with *Nature*. (*Scientific American* is part of Nature Publishing Group.) SA

JEAN-MARC CÔTÉ

Illustration by Nick Higgins

editors@sciam.com



April 2013

PRIVATIZATION'S PERIL

While S. Alan Stern rightly identifies "the advent of new, reusable suborbital vehicles" and technologies designed "with an eye to simplicity" as keys to cheaper spaceflight in "The Low-Cost Ticket to Space," he fails to explain why the same revolutions in technology could not be incorporated into traditional, governmental space programs. He ignores the fact that the leaps made by private space companies are largely attributable to inordinate investment by their starry-eyed and deep-pocketed backers. For the most part, they have not proved their financial sustainability.

Also, despite Stern's enthusiasm, space researchers should be wary of relinquishing control of technological developments. Privatizing spaceflight means the market will shape the field's evolution. And market forces are likely to pull spaceflight toward manned missions, which are more profitable but limited in scientific value.

Zachary Miller
Fleetwood, Pa.

"The leaps made by private space companies are largely attributable to inordinate investment; they have not proved their financial sustainability."

ZACHARY MILLER *FLEETWOOD, PA.*

ENERGY COSTS OF FUELS

"The True Cost of Fossil Fuels," by Mason Inman, gives measurements of the energy return on investment (EROI)—a calculation of energy provided per unit of energy spent—for fossil fuels and renewables.

It appears to me that issues with renewables that were not quantified are significant. For example: the need for storage or backup capabilities for wind and solar; the need for new transmissions systems to handle the typically remote locations for large-scale solar or wind projects; or the impact of battery production for electric vehicles. I wonder how the charts would look if they had been so modified.

Peter Gartman
Media, Pa.

Unlike the entry for corn, the calculation of the EROI for biodiesel from soy does not appear to include fertilizer as energy consumed during production. I raise soybeans on my farm, and although soy requires little or no nitrogen, full amounts of phosphorus and potassium are needed for reasonable yields, which would lower soy's EROI. Also, the production biodiesel from canola is worthy of much greater consideration. Canola produces about the same average yield per acre as soy, but whereas soy contains about 16 percent oil, canola contains about 44 percent.

David C. Brown
Shoemakersville, Pa.

NEUTRINO MASS

"Ghostly Beacons of New Physics," by Martin Hirsch, Heinrich Päs and Werner Porod, describes the search for the fundamental neutrino particle.

One of the difficulties in further characterizing the elusive neutrino is the question of its mass. As the article shows, observed beta decay results in emission of a single electron and antineutrino (or two when two decays occur simultaneously).

This, combined with the difficulty in obtaining an accurate measurement of the mass of the particles involved, leads me to wonder how accurate current measurements of the masses of the neutron, proton and electron are. If the mass measurements of these particles were accurate enough, a simple equation would result in the mass of the antineutrino.

If the current mass measurements of these basic particles are not sufficiently accurate, can a more accurate measurement be made with today's equipment?

Carl Gruel
Kilmarnock, Va.

PÄS REPLIES: Indeed, nuclear beta decay is being used to search for the neutrino mass. According to special relativity, though, energy and mass are equivalent. So the mass of the emitted antineutrino is not simply given by the neutron mass minus the proton and the electron mass; in addition, the kinetic energies of the emitted antineutrino and the electron enter the equation. What experimentalists do, then, is look at the maximum possible energy of the electron and check whether it can carry away all the missing energy in the budget above. If it doesn't, the difference corresponds to the neutrino mass.

Thus, the problem essentially boils down to a measurement of the electron energy. This is done with spectrometers, and a new experiment called KATRIN, with a huge spectrometer of 24 meters in length, is at present under construction in Karlsruhe, Germany.

NEIGHBORHOOD SPY

"The Spies above Your Backyard," by the Editors [Science Agenda], calls for Congress to proactively protect U.S. citizens from violations of privacy by the use of domestic drones by private citizens and government agencies such as law enforcement.

Your readers' privacy is less threatened by official drones than private ones. Toy stores and e-stores sell toy helicopters with cameras already built in, controlled by a smartphone. They can stream video live from your upstairs bedroom window. I doubt the feds or fuzz would bother peeping, but your neighbor or suspicious spouse might.

Paul J. Madden
Seatac, Wash.

HEAVENLY HALLUCINATIONS

In "Proof of Hallucination" [Skeptic], Michael Shermer purports to "prove" that near-death experiences (NDEs) are hallucinations. Unfortunately, his arguments only prove that hallucinations are real for many people, including mental patients. None of his presented data relates to NDEs. Neither can he answer the simple question: "If these near-death experiences are hallucinations, why is it then that all the NDE survivors are having *the same hallucination?*"

ALAN HUGENOT
San Francisco

SHERMER REPLIES: Hallucinations are by no means restricted to mental patients, which was the point of my examples from Oliver Sacks and from migraine sufferers who have hallucinations. As I document in my book The Believing Brain, *mountain climbers, solo sailors, ultramarathon athletes, long-distance truckers and many others experience hallucinations under a variety of conditions, including oxygen deprivation, physical trauma, brain injury, anesthesia and surgery. The evidence is overwhelming that NDEs are the product of the brain, just like all these other experiences people report having.*

So again, what's more likely: That NDEs are the neurological exception that happens to support our Western religious belief in heaven or that, like all other experiences, they are produced by our neurons under certain neurological conditions?

CLARIFICATION

In "Shock to the System" [The Science of Health], Maryn McKenna refers to sepsis as annually killing 260,000 people in the U.S. and as the 10th leading cause of death in the country. The former figure, used by Sepsis Alliance and several researchers, accounts for fatal cases of sepsis arising from any cause, including influenza, pneumonia and septicemia, which specifically denotes the invasion of the bloodstream by microorganisms. The ranking as the 10th leading cause of death refers to septicemia alone and is based on 1999 figures from the U.S. Centers for Disease Control and Prevention. Preliminary data from the CDC now ranks septicemia as the 11th leading cause of death in the U.S.

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/aug2013

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Opinion and analysis from *Scientific American*'s Board of Editors

Solitary Is Cruel and Unusual

Isolating inmates inflicts permanent mental harm. The practice must be curbed

Some 80,000 people are held in solitary confinement in U.S. prisons, according to the latest available census. The practice has grown with seemingly little thought to how isolation affects a person's psyche. But new research suggests that solitary confinement creates more violence both inside and outside prison walls.

Prisoners in solitary confinement—also known as administrative segregation—spend 22 to 24 hours a day in small, featureless cells. Contact with other humans is practically nonexistent. Because solitary confinement widely occurs at the discretion of prison administration, many inmates spend years, even decades, cut off from any real social interaction. More than 500 of the prisoners at Pelican Bay State Prison in California, for example, have been in isolation units for over a decade, according to the California Department of Corrections and Rehabilitation.

You might assume all inmates sent to solitary are the "worst of the worst"—rapists and murderers who continue their violent ways even behind bars. But in fact, many are placed in solitary for nonviolent offenses, and some are not even criminals, having been arrested on immigration charges. Others are thrown into isolation cells "for their own protection" because they are homosexual or transgendered or have been raped by other inmates.

Whatever the reasons, such extreme isolation and sensory deprivation can take a severe, sometimes permanent, toll on emotional and mental health. Researchers have found that prisoners in solitary quickly become withdrawn, hypersensitive to sights and sounds, paranoid, and more prone to violence and hallucinations. Craig Haney, a professor of psychology at the University of California, Santa Cruz, has documented several cases of individuals with no prior history of mental illness who nonetheless developed paranoid psychosis requiring medical treatment after prolonged solitary confinement. As damaging as the consequences are for otherwise healthy adults, they are even worse for adolescents, whose brains are still in their final stages of development, and the mentally ill, who already struggle to maintain a solid grasp on reality. About half of all prison suicides occur in isolation cells.

The U.S. justice system once understood that long stretches in solitary served no good purpose. In 1890 the U.S. Supreme Court addressed the pernicious nature of solitary confinement in the case of a man who had murdered his wife. In their decision, the justices noted that "a considerable number of the prisoners fell, after even a short confinement, into a semi-fatuous condition, from which it was next to impossible to arouse them, and others became violently insane; others still committed suicide, while those who stood the ordeal better were not generally reformed, and in most cases did not recover sufficient mental activity to be of any subsequent service to the community."

Nearly a century later this wisdom was all but lost. The use of solitary grew in the 1980s after white supremacists murdered two prison guards in the federal penitentiary at Marion, Ill. Officials responded by placing the entire facility on permanent lockdown. What started out as a stop-gap measure to address prison violence soon became institutionalized; so-called supermax prisons were built that encased all inmates in solitary cells whose only window was often just the slot for food found in the steel door.

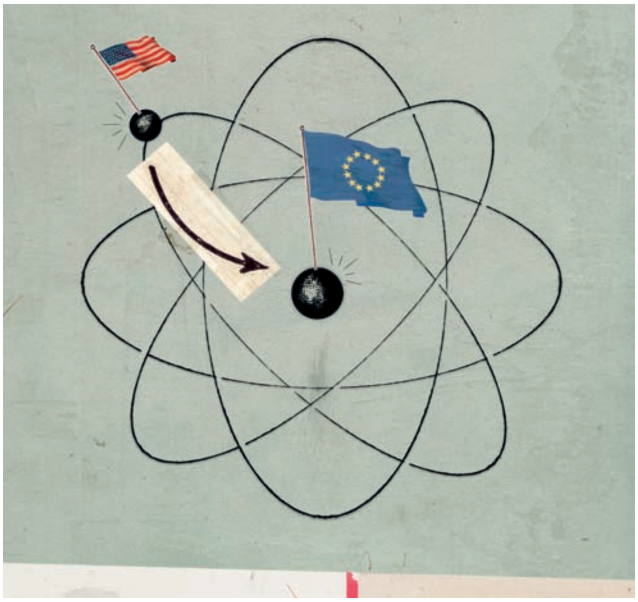
Yet strangely, no one knows if segregating prisoners reduces violence. Indeed, evidence suggests that the opposite is true. After the state of Mississippi reduced the number of prisoners in solitary confinement at its Parchman facility and developed new units for prisoners with mental illness, the number of violent attacks plummeted from a high of 45 in March 2006 to five in January 2008. (Mississippi also saved more than $5 million.) A 2007 study of Washington State's prison population found that 69 percent of those who were released directly to the community from solitary—a dishearteningly regular practice—committed new crimes that landed them back in jail within three years, compared with 46 percent of those who had been allowed to readjust to the general prison population before release.

Solitary confinement is not only cruel, it is counterproductive. The U.S. should reclaim the wisdom it once held and dramatically limit the practice. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/aug2013

Illustration by Eva Vazquez

Commentary on science in the news from the experts



Don Lincoln is a senior physicist at Fermilab in Batavia, Ill., and also does research at the Large Hadron Collider near Geneva. He is author of the popular 2009 science book *The Quantum Frontier*.

Beyond the God Particle

The death of particle physics in the U.S. has been greatly exaggerated

Physicists find God particle! That has become a common headline since the Large Hadron Collider (LHC) near Geneva began turning out data. Researchers have been more cautious and have completely disavowed the ridiculous name used for the Higgs boson, but we agree that the LHC indeed turned up a new particle last summer.

Another common conclusion from the LHC work is that the U.S., the world leader in physics for the past century, has passed the torch to Europe and that U.S. particle physics is doomed to decay. But there is no strong evidence to support this conclusion. The U.S. is still a leader in particle physics, and physicists are determined to keep it that way.

To be sure, the steady stream of updates in the saga of the Higgs boson is based on data from the LHC, which is funded largely by Europe. Even so, the imprimatur of U.S. physicists is indelibly stamped on each scientific paper. The two collaborations producing these results—ATLAS and CMS—are huge, with 6,600 physicists between them, of which 1,700 hail from 96 U.S. universities, national laboratories and other institutions. The U.S. scientific community has not abandoned particle physics research.

Nor should you think that these U.S. scientists are moving to Europe. By and large, these physicists are permanently stationed in the U.S. While we may fly to Switzerland for periods of time, we return to our families and jobs in America. In the heyday of the Fermilab Tevatron, the opposite was true. Scientists from Europe, Asia and other continents came to the American heartland before boarding a plane back home. Particle physics has long been an international endeavor, and scientists will travel to the laboratory that has the equipment they need. A migration of scientists in both directions continues today.

The shift to Europe in particle physics research is mainly economic. Any large installation is expensive, and the host country or region will reap the rewards of having the facility located inside their borders. To run a big accelerator requires engineers, programmers, technicians and a host of businesses to support them. Given the economic impact of such a large operation, it is entirely fitting that the host country foot the lion's share of the bill, as that money is plowed into the local economy. The LHC cost about $10 billion to build over many years. That money went into acquiring and installing the components necessary to do the desired experiments. The U.S. contribution to the construction of both the LHC and the detectors was $531 million, a sizable sum but only 5 percent of the total.

While American physicists work hard at LHC research, they also have exciting experiments in the U.S., some just getting under way. For example, among a broad network of national laboratories that investigate diverse questions of fundamental science, Fermilab's sole mission is to study the big questions of the universe. Between the existence of the LHC and Fermilab's budget decline over the past few years, hope is dwindling for a new accelerator in the U.S. with energy high enough to eclipse the LHC anytime soon. Still, the lab has been pursuing a dynamic research agenda, studying the behavior of neutrinos, probing detailed questions of the behavior of muons, studying dark matter and energy, improving and upgrading existing accelerators, and doing vigorous R&D on future accelerator technologies.

These are not mere placeholder efforts. If the U.S. were not pursuing them, the experiments would be done elsewhere because the questions are crucial to furthering our understanding of the universe. In fact, the laboratory's high-intensity experiments will be able to probe phenomena not accessible at the higher-energy LHC and will draw experimenters from all across the world.

This is not to say that the future of particle physics in the U.S. is rosy. The Department of Energy's budget for particle physics had been dropping for a decade when the economic downturn of 2008 accelerated the downturn, and continuing political turmoil in Washington makes for uncertain times.

The questions physicists ask about the origins of the universe and the nature of reality have puzzled thinkers for ages. In the U.S., we will continue to ask these big questions. And we expect to answer some of them. SA

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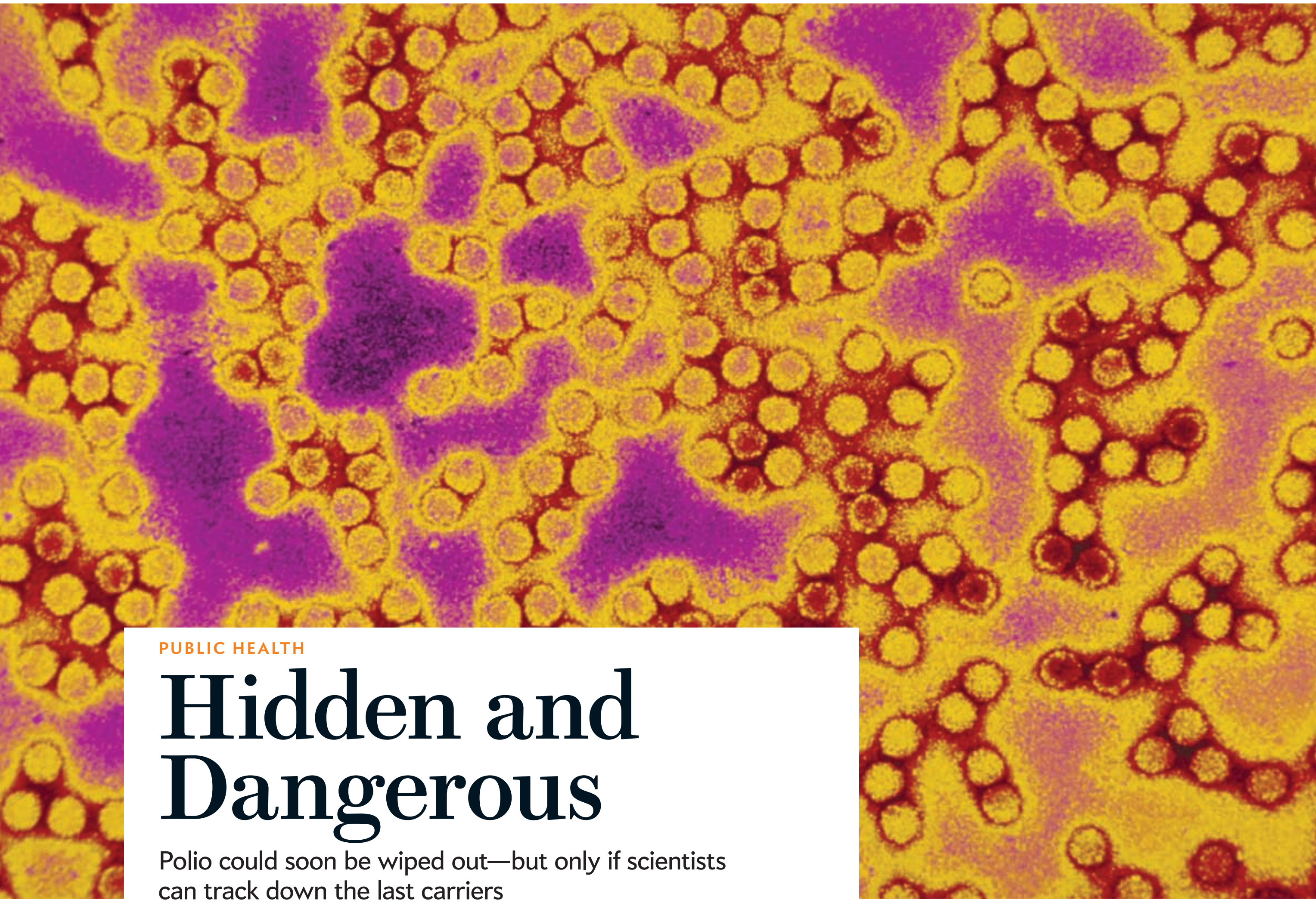
Illustration by Emmanuel Polanco

ADVANCES

Dispatches from the frontiers of science, technology and medicine



PUBLIC HEALTH

Hidden and Dangerous

Polio could soon be wiped out—but only if scientists can track down the last carriers

Global eradication of polio has been the ultimate game of Whack-a-Mole for the past decade; when it seems the virus has been beaten into submission in a final refuge, up it pops in a new region. Now, as vanquishing polio worldwide appears again within reach, another insidious threat may be in store from infection sources hidden in plain view.

Polio's latest redoubts are "chronic excreters," people with compromised immune systems who, having swallowed weakened polioviruses in an oral vaccine as children, generate and shed live viruses from their intestines and upper respiratory tracts for years. Healthy children react to the vaccine by developing antibodies that shut down viral replication, thus gaining immunity to infection. But chronic excreters cannot quite complete that process and instead churn out a steady supply of viruses. The oral vaccine's weakened viruses can mutate and regain wild polio's hallmark ability to paralyze the people it infects. After coming into wider awareness in the mid-1990s, the condition shocked researchers.

Philip Minor, deputy director of the U.K.'s National Institute for Biological Standards and Control, describes the biomedical nightmare: Wild polioviruses stop circulating. Countries cut back on vaccination efforts. A chronic excreter kisses an unvaccinated baby, and the baby goes to day care. "And zappo," he adds, "it's all over the place, with babies drooling all over each other. So you could see a scenario where polio would come back from a developed country." It could happen in the developing world as well. Although it was once thought that immunocompromised individuals could not survive for long in lower-income countries, circumstances are changing as those countries improve their health care systems. In 2009 an immunodeficient 11-year-old Indian boy was paralyzed by polio, five years after swallowing a dose of oral vaccine. It was only then that researchers recognized him as a chronic excreter.

Chronic excreters are generally only discovered when they develop polio after years of surreptitiously spreading the virus. Thankfully, such cases are rare. According to Roland W. Sutter, the World Health Organization scientist who heads research policy for the Global Polio Eradication Initiative, the initiative is pushing for the development of drugs that could turn off vaccine virus shedding. A few

GETTY IMAGES

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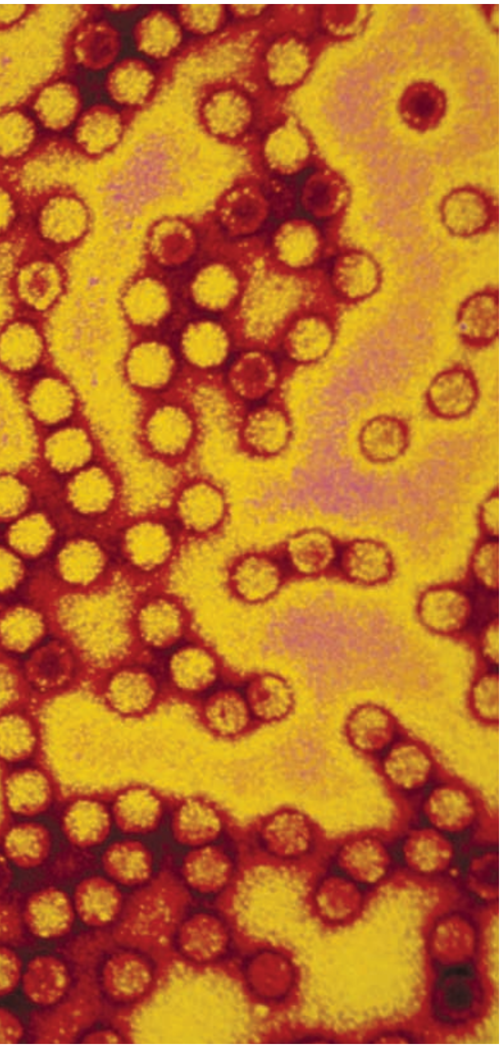


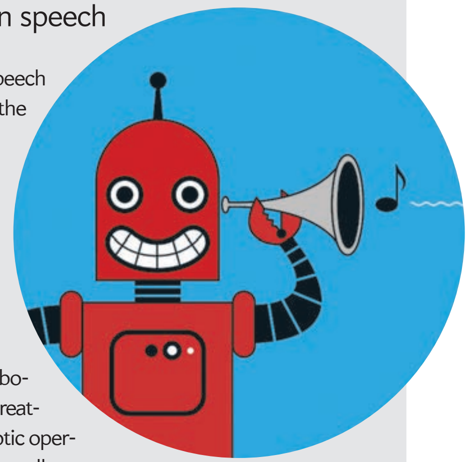
promising options are in the pipeline.

Drugs can only solve the problem if chronic excreters are identified, and that's no easy task. For years scientists in Finland, Estonia and Israel monitored city sewers, watching for signs of shedders' presence. In many samples, they have found the telltale viruses from chronic excreters, but they have failed to locate any of the individuals. These stealthy shedders may not be classic immunodeficient patients traceable through visits to immunologists. Instead they may be people who do not know they have an immunity problem at all and are under no specialized medical care. "We know that there's really a Damocles sword hanging over them," Sutter says. It hangs over the rest of us as well. —*Helen Branswell*

TECHNOLOGY

Lending Robots an Ear

A new approach allows "smart" machines to understand sounds other than speech



Robots can already discern and react to speech thanks to voice-recognition software such as the iPhone's Siri. But "smart" machines still struggle with most other sounds. "In some sense, it's almost a simpler problem, but there hasn't been a lot of work on noise in the environment," says roboticist Joseph Romano of Rethink Robotics in Boston. "It hasn't been in the loop for robotic feedback."

Now Romano is letting robots listen in on more than our conversations. He and his collaborators at the University of Pennsylvania have created a software tool called ROAR (short for robotic operating system open-source audio recognizer) that allows roboticists to train machines to respond to a much wider range of sounds. As described in a recent issue of *Autonomous Robots,* the tool's chief requirement is a microphone.

To begin training, the robot's microphone first captures ambient sounds, which ROAR scrubs of noisy static. Next the operator teaches ROAR to recognize key sounds by repeatedly performing a specific action—such as shutting a door or setting off a smartphone alarm—and tagging the unique audio signature while the robot listens. Finally, the program creates a general model of the sound of each action from that set of training clips.

The group tested ROAR on a one-armed robot, improving the machine's ability to complete specific tasks. In one scenario, the robot attempted to autonomously grasp and activate an electric drill. Without any sonic feedback, the robot only succeeded in nine out of 20 attempts, but its success rate doubled while using ROAR. If after grasping, the robot did not hear the whir of the electric motor, it adjusted its grip and tried again.

The next step is to ensure the system works in loud environments. Integrating audio into a robot's feedback loop alongside visual and tactile cues could someday allow robotic nurses to rapidly respond to cries for help or enable factory robots to react when something breaks. Although the technology is in early stages, Romano thinks the potential is enormous. "We haven't even begun to explore what we can do," he says. —*Gregory Mone*

BY THE NUMBERS

658

The average number of annual deaths in the U.S. attributed to extreme heat between 1999 and 2009—"more than tornadoes, hurricanes, floods, and lightning combined," according to the U.S. Centers for Disease Control and Prevention.

14,802: The number of people in France who died from an extreme heat wave in 2003, which took place during the hottest European summer since 1540.

Illustrations by Thomas Fuchs

CONSERVATION

The Art of Distraction

An undersea sculpture garden in waters around Cancun is saving a reef from tourist traffic

Managers of a national park in the sea around Cancun realized that traffic was taking its toll on the Manchones Reef. Some 87,000 divers annually swam in the clear, blue waters surrounding the reef. Scuba divers and tour boats battered and frightened the sea turtles, queen angelfish, spotted trunkfish and other reef creatures. After some trial and error, park director Jaime Gonzalez Canto landed on a solution: to redirect tourists to an alternative spectacle. He had British artist Jason deCaires Taylor create underwater sculptures that would perform double duty as an artificial reef. The Subaquatic Museum of Art opened in 2010.

The project got off to a rough start. At first, sea urchins swarmed over fuzzy films of green algae that grew on the figures, prompting tour operators to demand a cleanup. Gonzalez Canto compromised by cleaning half of the sculptures. That yielded a lesson in reef ecology. The sculptures stripped of algae-eating urchins rapidly regrew their vegetal patina (*below*). In contrast, the untouched sculptures soon blossomed with hard, protective layers of calcium carbonate generated by communities of organisms that slowly grew underneath the algae. The installation gradually became a microcosmic reef.

Today the installation and habitat feature more than 450 deepwater statues made of porous cement initially seeded just with fire coral. A dazzling diversity of corals, sponges and tropical fish is starting to cover the sculptures; as the statues disappear, a full reef is materializing in their place. Researchers at two Mexican universities are studying how the sculptures are transforming over time and the extent to which the museum is drawing tourists away from the troubled nearby reef.

"The challenge is to redirect the divers completely to the sculptures," Gonzalez Canto says. "If we can find a nice alternative—something that attracts tourists, not just for a day but two or three, maybe we can one day close these resources completely." The results will help to inform similar efforts around the globe. —*Erik Vance*

JASON deCAIRES TAYLOR

COMMENT AT ScientificAmerican.com/aug2013

Best of the Blogs

MEDICINE

Anxiety Can Be Good for You—Sometimes

Short-term stress can boost the immune system

Firdaus Dhabhar likes to film babies crying when they get their shots, but not for any sadistic reason. He believes that the wailing is a good sign. A Stanford University researcher who studies how stress changes the body, Dhabhar, along with his colleagues, has discovered that stressed-out laboratory mice exhibit more robust immune responses to vaccines than control groups of mice left in peace. Something similar happens to people. In a study of knee surgery patients, for example, Dhabhar found that the anxiety of their impending operations boosted the number of immune cells circulating in their blood. Such studies have convinced Dhabhar that stress does not entirely deserve its bad reputation and that in some situations it can actually improve health.

Dhabhar and his collaborators contrast the benefits of short-term stress with the consequences of chronic stress, which has long been known to suppress the immune system. Then again, chronic stress can also exacerbate allergies, asthma and autoimmune disorders in which the immune system is already overactive. So does stress excite or repress the immune system? Here is where things get frustratingly fuzzy, as they so often do in biology. It turns out that the answer hinges on the situation and the individual. A transient burst of stress tends to activate some parts of the immune system but not others; conversely, chronic stress generally stifles the entire immune system and can make it more likely to attack benign tissues.

In the knee surgery study, patients' immune systems did not all respond equally to anticipation of the operation. Some people showed an agile, adaptive response: the number of immune cells in their bloodstream peaked in the days before the operation, then decreased as those cells migrated to other tissues throughout the body. Other patients had a more sluggish maladaptive response: their levels of immune cells hardly wavered from baseline. As you might expect, those with adaptive immune responses recovered from surgery faster.

Most likely it will take decades of new research to gain a much deeper understanding of the biological mechanisms behind such individual differences. For now, though, we can at least be sure that it is okay to feel stressed when you get a shot—in fact, it's a good thing. *—Ferris Jabr*

Adapted from Brainwaves at blogs.ScientificAmerican.com/brainwaves

PALEONTOLOGY

Fact-Checking a Frozen Mammoth

How could the ancient carcass contain liquid blood?

Russian researchers recently announced a mind-blowing discovery: a 10,000-year-old woolly mammoth carcass containing blood that resists freezing even at −17 degrees Celsius. The Siberian Times quoted team leader Semyon Grigoriev of North-Eastern Federal University in Yakutsk as speculating that the blood contains "a kind of natural anti-freeze." An Agence France-Presse report, meanwhile, quotes Grigoriev as saying "this find gives us a really good chance of finding live cells," which would be a windfall for his institution's international project to clone a mammoth.

I wondered if it might be too good to be true. But according to the outside experts I contacted, this mammoth really is an incredible find. Some of the reported claims about it are questionable, however.

"They have not found any 'living cell'—at most they could hope to find what the cloning enthusiasts might call a cell with 'viable' DNA, meaning that it would be intact enough to use in the context of a cloning effort," explains Daniel Fisher of the University of Michigan. But he cautions that "in general, ancient DNA is highly fragmented and by no means 'ready to go' into the next mammoth embryo."

Kevin Campbell of the University of Manitoba doubts that circulating mammoth blood could resist freezing at −17 degrees C. Maybe, Campbell offers, the Russian team's liquid sample contains an antifreeze that was concentrated during the preservation. Or, he says, maybe antifreeze-secreting bacteria contaminated the sample.

As for cloning, Fisher thinks other research deserves priority. "For all I want to learn about the lives of mammoths, I have more confidence in our ability to generate new knowledge from the fossil record than in our ability to learn from cloned mammoths," he says. *—Kate Wong*

Adapted from Observations at blogs.ScientificAmerican.com/observations

GETTY IMAGES

ENERGY

The Coming Boom in Geothermal Fracking

The technology that revitalized gas drilling could start an entirely new energy boom

Vast reservoirs of heat are locked in the earth's interior, untapped. The ground underneath our feet holds so much heat that tapping only 2 percent of it could satisfy current annual U.S. energy use 2,000-fold for each and every year of the foreseeable future, according to an analysis from the Massachusetts Institute of Technology. Fracking, the same technology used to drill for natural gas, may provide an economical way to get at that geothermal energy.

The idea is simple: Pump water or other fluids down deep beneath the surface. Hot rocks at depth boil the water into steam, which rises back to the surface to spin a turbine and generate electricity. In regions with hot rocks and plentiful water near the surface, building massive power plants is straightforward. But such optimal sites are few and far between. Fracking, which is the technique of fracturing passages in subterranean rock, can help. The same fractures that send natural gas streaming out from deep wells also allow geothermal heat to be tapped from practically anywhere on earth.

The U.S. Geological Survey estimates at least 500 gigawatts of electricity-generating capacity could be harvested this way—or 1.5 times more than the entire U.S. fleet of coal-fired power plants. That immense potential is why the Department of Energy invested $5.4 million to help geothermal specialists Ormat Technologies create the nation's first fracking-enhanced geothermal system (EGS). The company's Desert Peak power plant started spinning out electricity in April near Reno, Nev. Other EGS plants are already operating in Europe and Australia.

"The big prize is EGS," enthuses Douglas Hollett, an oil industry veteran now heading the DOE's geothermal technologies office. "The key is learning how to do it in a reliable way, in a responsible way."

As it stands, geothermal produces "less than one percent of global energy," notes a recent perspective in *Science.* The reason for this dearth is simple: money. In addition to the years-long, multimillion-dollar expense of building a power plant on top of any viable wells, there is also the $6-million to $8-million risk of prospecting and drilling a dry hole—a well that does not produce steam. Drill too many dry holes, and you'll go bankrupt before generating and selling a single watt of power.

If technologies can be developed to reduce the risks, geothermal could play a more prominent energy role. With that in mind, the DOE is pursuing better methods for geothermal prospecting, drilling and fracking. Because much of that work could also benefit traditional drilling, the oil and gas industry may actually help foot the bill for enhanced geothermal technology. As Hollett says, "We know that has to tie into what we do." *—David Biello*

BY THE NUMBERS

400

The age in years of frozen moss that University of Alberta researchers resurrected in 2009. Their results challenge the idea that glaciers—such as the one in which the moss was contained—annihilate all plant life.

32,000

The age in years of seeds germinated by Russian scientists in 2012 from a Siberian flowering plant. The seeds were found deep below permafrost, suggesting that our coldest climates harbor untapped stocks of genetic material.

COMMENT AT ScientificAmerican.com/aug2013

DO THE MATH

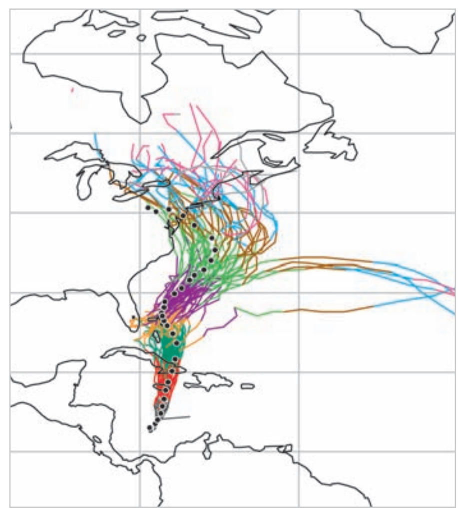
Computing Superstorm Sandy

The mathematics of predicting a hurricane's path

Many early forecasts for Hurricane Sandy last year predicted that the system would fizzle over the Atlantic. Yet a model developed by researchers at the European Center for Medium-Range Forecasts showed a more alarming scenario: the storm would instead turn west to threaten the Eastern Seaboard. The model's refined predictions pinpointed the hurricane's landfall around the New Jersey area in time to allow residents to seek higher ground. The key to the more accurate forecast involved mathematical mastery of the storm's chaotic behavior.

Weather forecasts are calculated with computers that solve equations involving variables such as wind speed, pressure, temperature, air density and humidity. If the earth somehow possessed just one weather system, our fist shaking at forecasts could end. Instead, of course, the planet harbors many systems that intermix across boundaries and scales, making forecasting a tangled problem.

In the case of Sandy, forecasters monitored a higher-order variable called potential vorticity, a measure of a weather system's swirl, to help predict the storm's future development. A crucial ingredient for Sandy's devastating landfall proved to be an enhancement of this swirl measure caused by a trough of low-pressure air that was thousands of miles away in the northeastern Pacific when the tropical depression first formed. As Sandy moved north from the Caribbean, the distant trough traveled east across the U.S. on what turned out to be a collision course.



Ensemble of forecasts shows Sandy's predicted swerve and the likely regions where landfall would occur; the dotted line is the actual track of the storm.

COURTESY OF EUROPEAN CENTER FOR MEDIUM-RANGE WEATHER FORECASTS

On October 29 Sandy's warm, moist air began to rise as it approached the trough's cooler air, whipping up stronger winds. As the two weather systems coiled around each other, Sandy surged in strength and curved toward the nation's northeastern shoreline, just as the European researchers had foreseen. The ultimate accuracy of the group's forecasts about a week before Sandy's landfall can be attributed to the success of its model in predicting and capturing the interaction between these weather systems.

The step-by-step quantification of this stormy choreography was accomplished solely through the careful application of mathematics. By predicting Sandy's landfall, in a very real sense, the European team's math helped to save American lives.

—Ian Roulstone and John Norbury

Roulstone and Norbury are authors of Invisible in the Storm: The Role of Mathematics in Understanding Weather *(Princeton University Press).*

COMMENT AT ScientificAmerican.com/aug2013

LAB NOTES

Medicine's Most Minuscule Frontier

A bioengineer sculpts medical devices at the nanoscale

All creatures struggle with a common problem: they must let in nutrients and vent wastes while also keeping pathogens and poisons out. At a cellular level, humans and other vertebrates safeguard their bodies using "tight junctions," watertight bonds between adjacent cells. Tight junctions are in almost all our tissues and even help waterproof our skin. But they also make it very difficult for drugs to get into the body's tissues from the outside world.

Nanoscale and microscale drug-delivery devices as small as a few atoms or as large as the width of a human hair can interact with tight junctions and other cellular features to more effectively administer drugs to patients. For example, we have developed a tiny film with nanoscale wire-shaped features that cells like to grab onto. The film activates certain chemical pathways in the cells that alter cell membrane structure and prop open the tight junctions. That allows doctors to use reduced, less dangerous doses of highly toxic anticancer drugs or to get more of a drug to a certain part of the body. For example, particles to treat diabetes could stick to the intestinal wall and release insulin over time rather than quickly flushing out of the body.

One device we are developing is for age-related macular degeneration, which causes blindness if left untreated. Right now patients go to the doctor and have a needle poked into their eye once a month to deliver the drug. Our nanoscale device can be delivered in a single injection, and it lasts from six months to a year. It would sit in the back of the eye and deliver the drug over time through microscopic pores, then dissolve away once it is emptied.

In the future, we will see particles with nanoscale parts that can not only target specific sites but also improve a drug's absorption within the body by prying open tight junction barriers.

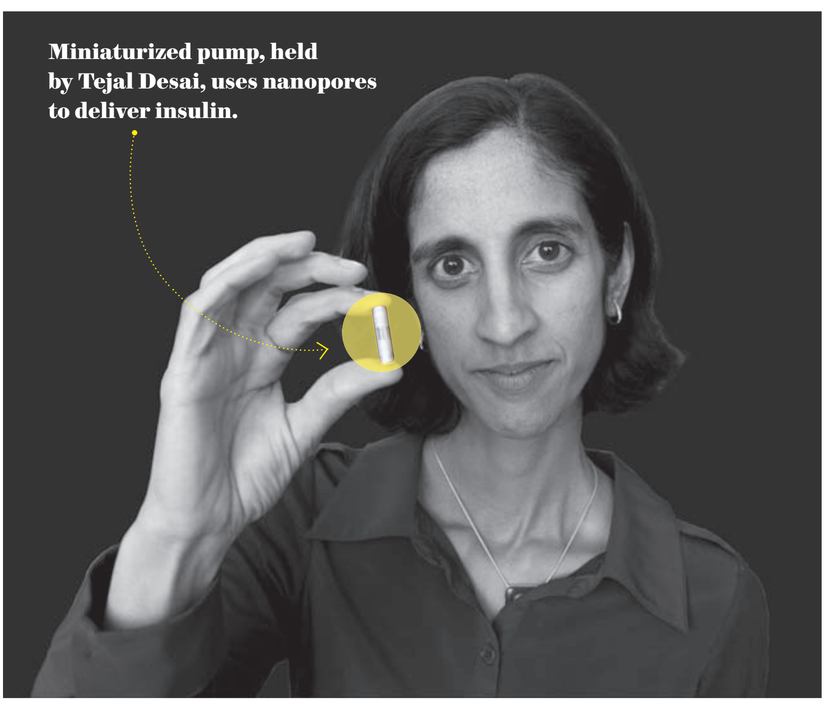
—As told to Marissa Fessenden

PROFILE

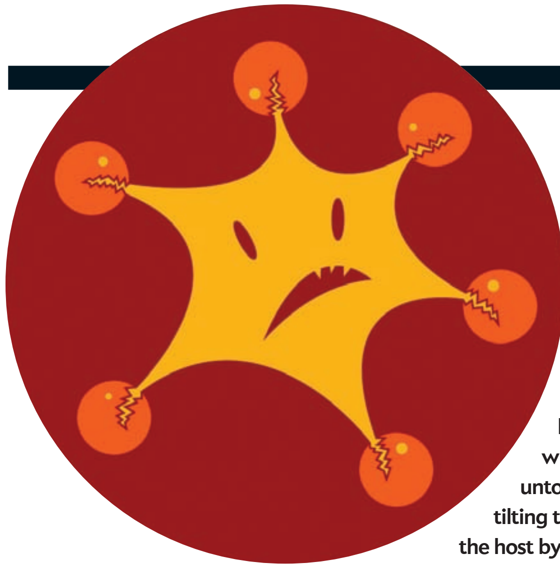
NAME
Tejal Desai

TITLE
Professor of bioengineering and therapeutic sciences

LOCATION
University of California, San Francisco


Miniaturized pump, held by Tejal Desai, uses nanopores to deliver insulin.

CINDY CHEW



MEDICINE

Bug vs. Superbug

Hungry microbes can hunt down drug-resistant superbugs

Scientists are turning to predatory bacteria to defeat drug-resistant infections. Microbiologists led by Daniel Kadouri, now at Rutgers University, lately have focused on two such predators—*Micavibrio aeruginosavorus,* which latches onto a germ and sucks out its innards, and *Bdellovibrio bacteriovorus,* which burrows into and parasitically reproduces within its prey. Kadouri's group previously showed that both species could kill dangerous microbes, but the predators had not been conclusively tested on drug-resistant strains. Thus, the team decided to unleash each species onto cell cultures of 14 drug-resistant varieties of bacteria commonly found in hospitals, then observed as the hunters wiped out large numbers of the pathogens. The results appeared online May 1 in the journal *PLOS ONE.*

But would the hunters attack human cells as well? In a study published in *PLOS ONE* on June 18, Kadouri's team found the microbes could kill bacteria linked with eye infections while leaving human eye cells untouched. "Exploiting nature, tilting the balance in the favor of the host by a means other than antibiotics, is a really important approach," says Daniel Zurawski, a microbiologist at the Walter Reed Army Institute of Research who studies drug-resistant bacteria.

Every year nearly two million patients acquire infections—often caused by drug-resistant germs—in hospitals in the U.S. alone, according to the Centers for Disease Control and Prevention. Even potent new antibiotics cannot wholly solve this problem, because colonies of virulent germs often encase themselves in biofilms—microscopic layers of protective slime that adhere to almost any surface. Previous work by Kadouri and others has found that predatory bacteria can infiltrate biofilms to kill the microorganisms inside, offering a new method of preventing infection.

Because of the potential sensitivity of an individual's immune system to microbes swimming around the bloodstream, Kadouri thinks the best predatory-bacteria treatment plan "is to apply them onto surface wounds or burns." He and his colleagues are now trying these therapies on live animals, with an eye toward eventual human trials. *—Charles Q. Choi*

PATENT WATCH

Fluorescence detection of poison oak oil: Tens of millions of Americans suffer every year after close encounters with urushiol, the oily allergen in poison oak and poison ivy. The barest brush of urushiol-tainted foliage, clothing or fur against the skin is often all that is needed to set off a severe allergic reaction, and by the time itching sets in, it is too late to avoid a rash. After experiencing a particularly nasty run-in with poison oak, Rebecca Braslau of the University of California, Santa Cruz, decided to fight back—with science. "I was thinking, 'I'm a chemist—I should be able to do something with this,'" she recalls. Patent no. 8,389,232 B2 details her invention, a substance that fluoresces in the presence of urushiol and gives an early warning to wash the allergen off. "It's a spray that you can put on clothing and tools," Braslau says. "Then you can hold the sprayed areas up to a fluorescent light to see the oils—they glow blue." She plans to test it on human skin soon. The invention, Braslau says, could help hikers, firefighters, rescue workers, farmers and anyone else who spends time outdoors. *—Arielle Duhaime-Ross*

THINKSTOCK

ASTRONOMY

Phantom Planets

Why hyperactive stars are planet hunters' biggest headache

Planet hunters have dramatically improved their techniques in the two decades since first discovering worlds beyond our solar system, most of which were gas-giant scorchers. Now they are searching for small, Earth-size exoplanets, such as the one said to circle Alpha Centauri B, which recently made headlines. Yet optimism about finding such planets may be premature. The problem is that stars swarm with surface activity that can mask or mimic the signs of tiny exoplanets. The putative planet orbiting Alpha Centauri B may, in fact, only be a mirage of stellar jitter.

Astronomers found the planet with a standard technique. Xavier Dumusque of the Harvard-Smithsonian Center for Astrophysics (CfA) and his colleagues monitored the star's light for periodic shifts in frequency, a sign that a planet's gravitational tug is causing the star to wobble.

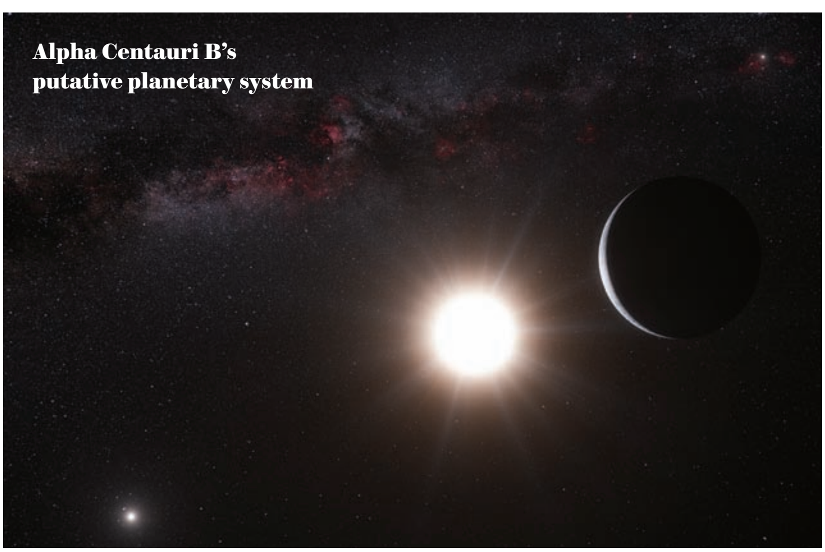
When Artie Hatzes, an astronomer at the Thüringian State Observatory in Tautenburg, Germany, reanalyzed the data with two different methods, he found conflicting results: one showed a wobble; the other found none at all. He described his work in a June issue of the *Astrophysical Journal.* "If one analysis produces a planet and another doesn't, that's not robust," he says. (To be fair, Dumusque and his team flagged significant uncertainties in their announcement last October.)

Alpha Centauri B's disputed world is not the first to come under close scrutiny. In 2010 an international team announced the discovery of a small planet around the star Gliese 581, smack-dab in the middle of the star's Goldilocks zone—the region where temperatures are just right for plentiful liquid water. Yet other researchers looking through their own data found no sign of the planet. Many other candidate detections are just as marginal, says David Latham, a planet-hunting veteran at the CfA, but remain unpublished.

The growing catalogue of hazy claims suggests that researchers must gather more data and resist the pressure to publish Earth-analogue discoveries too early, Hatzes says. He knows from experience: he now suspects that a planet his team announced in 2009, a gas-giant world thought to circle the star 42 Draconis, might also be a noise-induced illusion.

Going forward, Latham notes, planet hunters should focus on quieter stars and develop new models for sources of stellar jitter. Better spectrographs, such as the new HARPS-North on the island of La Palma in the Canary Islands, will help by reducing instrumental noise. Even so, Hatzes says, "at some point you're going to hit that wall, which is the noise level of the star."

—Ron Cowen



Alpha Centauri B's putative planetary system

COURTESY OF L. CALÇADA ESO AND NICK RISINGER *skysurvey.org (artist's conception)*

MICROBIOLOGY

A Microbial Mystery

Scientists still don't know exactly how antibiotics work

Microbes are tricky critters. Scientists long thought that antibiotics killed bacteria in diverse and specific ways—some prevented bacterial DNA from replicating; others impaired bacterial protein synthesis. Not so, said James Collins, a biomedical engineer at Boston University. In 2007 he published findings that these targeted mechanisms were not the cause of bacterial death after all. His team's study suggested that antibiotics kill by a common mechanism: they boost bacterial levels of molecules known as reactive oxygen species, which fatally corrode the organisms' DNA.

Now Collins's theory is under siege. In March, two independent teams, publishing in *Science*, showed that antibiotics kill bacteria under oxygen-deprived conditions, which, if Collins is correct, would be impossible: the production of reactive oxygen species depends on oxygen. The two groups also found that bacteria genetically engineered to lack intrinsic antioxidants—substances that protect against reactive oxygen species—are no more sensitive to antibiotics than normal bacteria.

What could explain these discrepancies? A May commentary in *Nature Biotechnology* posits that because the teams each used different flasks and protocols, batches of bacteria may have been exposed to different oxygen levels, potentially invalidating their findings. Other studies suggest a molecular marker the Collins group used to flag reactive oxygen species is flawed because it also lights up in the presence of other harmless molecules. Colin Manoil, a genome scientist at the University of Washington, worries that the Collins group may simply have misinterpreted its results. "There is a cause-and-effect problem," Manoil says—even if reactive oxygen species are produced in dying bacteria, they may be the result of impending death, not a cause of it.

The debate is a reminder that even microbes can be unpredictably complex. "Sometimes we fall back on experimental approaches that are not as specific as we would like them to be," says James Imlay, a University of Illinois at Urbana-Champaign microbiologist and co-author of one of the *Science* papers. "We're still groping at the edge of the darkness sometimes." —*Melinda Wenner Moyer*

Maryn McKenna is a journalist, a blogger and author of two books about public health. She writes about infectious diseases, global health and food policy.

EVAN KAFKA *Getty Images*

Rethinking Rabies

Some rabies infections may not be lethal, but be especially wary of dog bites

Last year a team of researchers from Peru and the U.S. made a discovery that challenged one of the most widely held assumptions about rabies—that the virus is nearly always fatal unless doctors administer a vaccine before it reaches the brain. Based on the results of blood tests, the scientists learned that half a dozen villagers in a remote part of the Peruvian Amazon had previously been infected—probably through bites from vampire bats, which are common in the area. But instead of suffering the agonizing deaths for which rabies is infamous, the villagers had recovered and apparently developed immunity to further infection.

The discovery put the Peruvians on a short list of people who have survived rabies without a vaccine. The best-known member of that select group is Jeanna Giese, a Wisconsin teenager who lived through the disease in 2004, also after contact with a bat. Out of desperation, Giese's physician improvised a risky treatment that included putting the girl into a controlled coma, which apparently allowed her body enough time to destroy the microscopic intruder. Doctors have since refined the treatment, now known as the Milwaukee protocol, and tried it on at least 39 other never vaccinated patients. Five more people have survived.

The mixed success rates, and the 2012 Peruvian study, underscore how little scientists know about rabies, despite its long history as a menace to humanity. Based on accumulating evidence, though, researchers now recognize that not all rabies infections are equal or universally fatal. Many different animals, including dogs, bats, foxes and raccoons, carry various strains of the rabies virus. The varieties hosted by bats and foxes appear to be weaker, and some people's immune systems may be able to defeat them without a vaccine. Dogs, however, carry a more virulent strain that has rarely been vanquished without medical intervention. To this day, canines remain the largest and most dangerous group of rabies carriers worldwide.

Even if doctors one day perfect a treatment for the later stages of rabies, the procedure would likely be complicated and expensive. Most public health experts think that the best way to control rabies is to vaccinate the most dangerous hosts: all domestic and stray dogs, particularly in the developing world. One such veterinary program in the Philippines has dramatically reduced deaths among humans, and others are under way in India and Tanzania.

DREADED DISEASE

RABIES KILLS about 55,000 people every year worldwide—an admittedly smaller toll than, say, AIDS or influenza. The virus's horrific reputation is nonetheless richly deserved. Symptoms emerge slowly in anywhere from a few weeks to—in rare cases—more than a year after contact with a rabid animal. The rabies virus crawls from nerve cell to nerve cell, eventually making its way from the site of the bite or wound to the brain. Fatigue, fever and chills gradually give way to hallucinations, anxiety, violent convulsions and the telltale foaming at the mouth once the virus reaches the salivary glands. Death is painful and terrifying, which is why standard medical practice calls for keeping patients sedated in the last phases of the disease.

Louis Pasteur's development of a rabies vaccine in 1885 prevented such gruesome outcomes if doctors acted quickly. (More than a century later most rabies deaths in the industrial world—including one or two each year in the U.S.—occur because a bite was not recognized or not taken seriously.) But his success had an unintended consequence: as explained in the 2012 book *Rabid: A Cultural History of the World's Most Diabolical Virus* (Viking Adult), rabies became a low priority for the budding field of biomedical research.

So when 15-year-old Giese entered Children's Hospital of Wisconsin in Milwaukee in 2004 with full-blown rabies, one month after a bite from a bat flitting around her church, there was still no successful treatment. She was feverish, semiconscious and jerking involuntarily.

Her physician, Rodney E. Willoughby, Jr., a pediatric infectious disease specialist, had never seen a case of rabies. He scoured the scant medical literature and found a gleam of hope: an experiment in which keeping rats anesthetized somehow allowed them to recover from a rabies infection. The rabies virus disrupts the usual electrical and chemical communication between neurons in the brain stem, which in turn loses its ability to regulate the heart and lungs. Perhaps, Willoughby reasoned, effectively silencing the brain with general anesthetics—while keeping the patient alive with a heart-bypass machine and mechanical ventilator—would buy the immune system enough time to destroy the virus. He decided to try it.

Against all odds, the therapy succeeded. Giese survived the viral storm, although she suffered some brain damage and spent two years relearning how to speak, stand and walk. She graduated from college in 2011 and now works as an animal caretaker and motivational speaker. Meanwhile Willoughby has continued to tinker with his intervention. But even he admits that the procedure is not a viable option for most clinics, because it demands so many resources.

Public health experts agree that the most effective way to deal with rabies is not inventing last-minute treatments such as the Milwaukee protocol but rather stopping rabies at its source: dogs.

In fact, some researchers wonder whether the Milwaukee protocol is truly effective at all. These naysayers have proposed that the real secret to at least some patients' survival is the fact that they were bitten by animals other than dogs that transmit either very tiny doses of rabies virus or strains that the human immune system can clear on its own.

CANINE CARRIERS

WHILE DOCTORS DEBATE whether the Milwaukee protocol works, public health experts agree that the most effective way to deal with rabies is to stop the disease at its source. Globally, domesticated and stray dogs are responsible for nearly all the 55,000 rabies deaths every year, according to the World Health Organization. The burden tends to fall most heavily on people (especially children) in rural areas, which have limited access to the rabies vaccine given annually to more than 15 million people to try to prevent the illness after someone has been exposed.

That leaves preventing rabies in dogs as the best option for reducing the number of deaths in humans. On a purely economic basis, mass dog vaccination certainly makes sense. Canine vaccines are not only less expensive than injections for people, they are far less expensive than critical care treatment of a human rabies case. But it can be difficult, politically speaking, to get anyone to pay attention to the health and welfare of dogs when people's needs remain so much more obvious in so many parts of the world, says Charles Rupprecht, formerly rabies chief at the U.S. Centers for Disease Control and Prevention and now director of research at the nonprofit Global Alliance for Rabies Control (GARC). "Medicine addresses human health issues, and agriculture addresses livestock—dogs are neither," he says. "It takes vision to see that this is a public health problem: you vaccinate dogs, human rabies cases come down, and you can put your public health dollars toward other goals."

Despite the daunting numbers—by one estimate the world count of stray dogs is 375 million—GARC researchers believe that dog vaccination programs are logistically feasible, and they have established pilot projects in Africa and Asia (some with support from the Bill & Melinda Gates Foundation). On the Philippine island of Bohol (human population: 1.3 million), researchers vaccinated an estimated 70 percent of the dog population. Before 2007 about 10 people died from rabies each year; since 2008 only one person has died of the disease.

Persuading people to vaccinate their pets is not always easy. Dealing with stray dogs is even more challenging. Because of a relentless rise in the number of rabies deaths in rural China, mostly in the south, that country has organized several mass killings of dogs, which disease-control experts and animal-rights activists have harshly criticized. Even if the cullings are effective in the short term, the stray populations inevitably rebound, as will the virus. Meanwhile the popularity of keeping dogs as pets—around half of which may be unvaccinated—continues to increase as Chinese workers become more prosperous.

Perhaps vaccinating dogs will seem like a more workable plan once researchers figure out how to do away with injections, which require rounding up animals, as well as proper refrigeration and storage of the inoculations. A few especially promising projects spread food pellets laced with vaccines, similar to the blocks of treated fishmeal that have been used to control raccoon rabies in the U.S. Some of the food pellets also include sterilizing contraceptives to reduce numbers of unvaccinated newborns and shrink the size of stray populations.

Rupprecht points out that if such vaccines, still in development for dogs, can be commercialized, they would find a ready market in China and India, the countries with the largest populations of strays and the most deaths from rabies. The necessary business know-how and technical acumen are already in place: China and India happen to be the biggest vaccine-manufacturing countries in the developing world. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/aug2013

David Pogue is the personal-technology columnist for the *New York Times* and an Emmy Award–winning correspondent for *CBS News*.

The Last Thing You'll Memorize

Have smartphones in every pocket made memorization obsolete?

When my father was growing up, his father offered him 25 cents to memorize the complete list of U.S. presidents. "Number one, George Washington. Number two, John Adams …"

A generation later my dad made the same deal with me, upping the reward to $5. (The prize had grown, he explained, "because of inflation and because there are more presidents now.")

This year I offered my own son $10 to perform the same stunt. My son, however, was baffled. Why on earth should he memorize the presidents?

Nowadays, he argued, "everybody has a smartphone" and always will. He'll probably turn out to be correct; 2013 is a tipping point, in which, for the first time in history, smartphones will outsell plain ones.

In other words, having a computer in your pocket is the norm. Google is always one tap away. So there's very little sense, as far as my son is concerned, in memorizing anything: presidents, the periodic table of the elements, the state capitals or the multiplication tables above 10.

Now, parents in my generation might have a predictable reaction: dismay and disappointment. "Those young kids today! Do we have to make everything easy?" we say. "If they don't have enough facts in their heads, they won't be able to put new information into context."

That's an understandable argument. On the other hand, there is a powerful counterargument: As society marches ever forward, we leave obsolete skills in our wake. That's just part of progress. Why should we mourn the loss of memorization skills any more than we pine for hot type technology, Morse code abilities or a knack for operating elevators?

Maybe memorization is different than those job skills. Maybe having a store of ready information is more fundamental, more important, and thus we should fight more fiercely to retain it.

And yet we've confronted this issue before—or, at least, one that is almost exactly like it. When pocket calculators came along, educators and parents were alarmed about students losing the ability to perform arithmetic using paper and pencil. After hundreds of generations of teaching basic math, were we now prepared to cede that expertise to machines?

Yes, we were. Today calculators are almost universally permitted in the classroom. You are even allowed to use one—encouraged, in fact—when you are taking the SAT.

In the end, we reasoned (or maybe rationalized) that the critical skills are analysis and problem solving—not basic computation. Calculators will always be with us. So why not let them do the grunt work and free up more time for students to learn more complex concepts or master more difficult problems?

In the same way, maybe we'll soon conclude that memorizing facts is no longer part of the modern student's task. Maybe we should let the smartphone call up those facts as necessary—and let students focus on developing analytical skills (logic, interpretation, creative problem solving) and personal ones (motivation, self-control, tolerance).

Of course, it's a spectrum. We'll always need to memorize information that would be too clumsy or time-consuming to look up daily: simple arithmetic, common spellings, the layout of our hometown. Without those, we won't be of much use in our jobs, relationships or conversations.

But whether we like it or not, we may as well admit that the rest of it will probably soon go the way of calligraphy, the card catalogue and long division. Whenever we need to access abstruse facts, we'll just grab our phones—at least until we implant even better technologies right into our brain. SA

SCIENTIFIC AMERICAN ONLINE
Six ways that brains trump tech: ScientificAmerican.com/aug2013/pogue

Illustration by Shaw Nielsen

Giulio Tononi and **Chiara Cirelli** are professors of psychiatry at the University of Wisconsin-Madison. Their research on the function of sleep is part of a larger investigation of human consciousness, the subject of Tononi's recent book *Phi: A Voyage from the Brain to the Soul* (Pantheon, 2012).

NEUROSCIENCE

Perchance to Prune

During sleep, the brain weakens the connections among nerve cells, apparently conserving energy and, paradoxically, aiding memory

By Giulio Tononi and Chiara Cirelli

EVERY NIGHT, WHILE WE LIE ASLEEP, BLIND, DUMB AND ALMOST PARALYZED, OUR brains are hard at work. Neurons in the sleeping brain fire nearly as often as they do in a waking state, and they consume almost as much energy. What is the point of this unceasing activity at a time when we are supposedly resting? Why does the conscious mind disconnect so completely from the external environment while the brain keeps nattering on?

The brain's activity during rest likely serves some essential function.

IN BRIEF

Sleep must serve some vital function because all animals do it.

Evidence suggests that sleep weakens the connections among nerve cells, which is a surprising effect, considering that strengthening of those connections during wakefulness supports learning and memory.

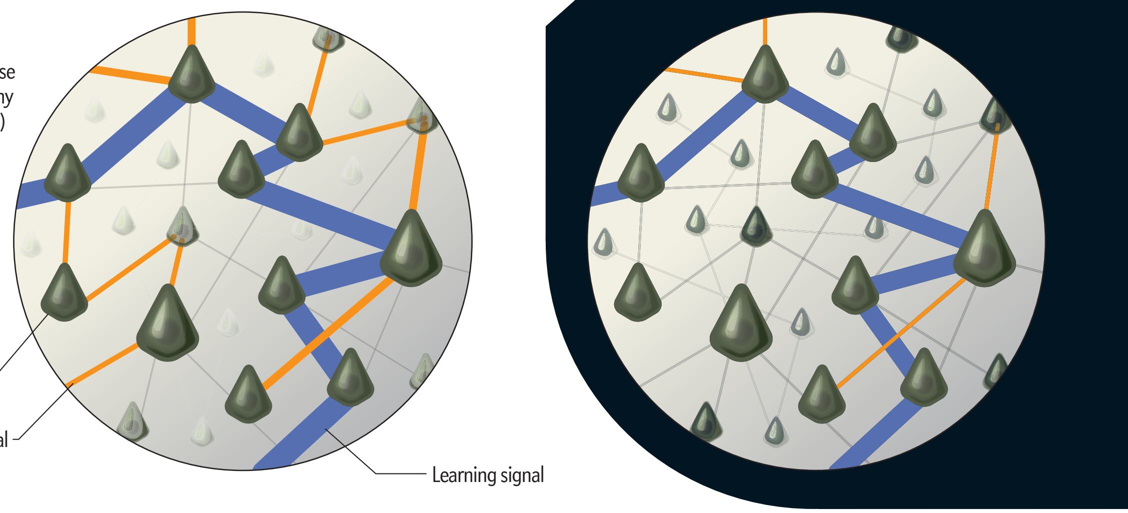
But by weakening synapses, sleep may keep brain cells from becoming oversaturated with daily experience and from consuming too much energy.

Photograph by Fredrik Broden

NEW HYPOTHESIS

Why We Sleep

When we are awake, memories form as neurons that get activated together strengthen their links (*below left*). Sleep researchers have assumed that during sleep, reactivation of these neuronal circuits reinforces the links. But just the opposite may occur (*panel at right*): mounting evidence suggests that spontaneous firing during sleep may weaken the synapses, or contact points, between neurons in many roused circuits. Such weakening, the authors propose, would return the synapses to a baseline level of strength—a change that would conserve energy in, and reduce stress on, nerve cells. This return to baseline, called synaptic homeostasis, could be the fundamental purpose of sleep.



The evidence for this importance starts with sleep's ubiquity. All animals apparently sleep even though being unconscious and unresponsive greatly raises the risk of becoming another creature's lunch. Birds do it, bees do it, iguanas and cockroaches do it, even fruit flies do it, as we and others demonstrated more than a decade ago.

Furthermore, evolution has devised a few extraordinary adaptations to accommodate sleep: dolphins and some other marine mammals that must surface often to breathe, for example, sleep by alternately switching off one hemisphere of their brain while the other remains in a waking state.

Like many scientists and nonscientists, the two of us have long wondered what benefit sleep provides that makes it so crucial to living creatures. More than 20 years ago, when we worked together at the Sant'Anna School of Advanced Studies in Pisa, Italy, we began to suspect that the brain's activity during slumber may somehow restore to a baseline state the billions of neural connections that get modified every day by the events of waking life. Sleep, in this telling, would preserve the ability of the brain's circuitry to form new memories continually over the course of an individual's lifetime without becoming oversaturated or obliterating older memories.

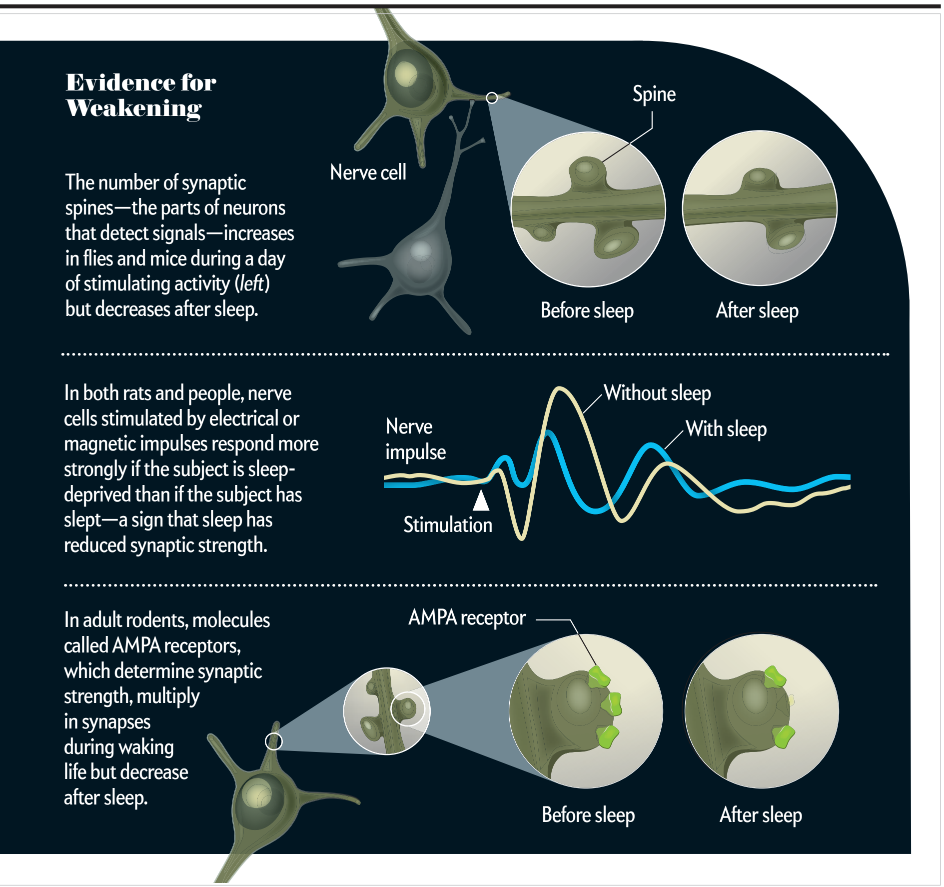
We also have an idea of why awareness of the external environment must be shut off during sleep. It seems to us that conscious experience of the here and now has to be interrupted for the brain to gain the chance to integrate new and old memories; sleep provides that respite.

Our hypothesis is somewhat controversial among our fellow neuroscientists who study sleep's role in learning and memory because we suggest that the return to baseline results from a weakening of the links among the neurons that fire during sleep. Conventional wisdom holds, instead, that brain activity during sleep *strengthens* the neural connections involved in storing newly formed memories. Yet years of research with organisms ranging from flies to people lend support to our notions.

SCHOOL OF NOD

SCIENTISTS first proposed the idea that sleep is important to memory nearly a century ago, and plenty of experiments since then have shown that after a night of sleep, and sometimes just a nap, newly formed memories "stick" better than they would if one had spent the same amount of time awake. This pattern holds for declarative memories, such as lists of words and associations between pictures and places, as well as for procedural memories, which underlie perceptual and motor skills, such as playing a musical instrument.

The evidence that sleep benefits memory led scientists to look for signs that the brain rehashes newly learned material at night. They found them: studies performed over the past 20 years, first in rodents and then in humans, show that patterns of neural activity during sleep sometimes do resemble those recorded while subjects are awake. For example, when a rat learns to navigate a maze, certain neurons in a part of the brain called the hippocampus fire in specific sequences. During subsequent sleep, rats "replay"



these sequences more often than predicted by chance.

Because of such findings, many researchers came to assume that sleep "replay" consolidates memories by further reinforcing synapses—the contact points between neurons—that have been strengthened when an individual is awake. The idea is that, as linked neurons fire repeatedly, the synapses connecting them more readily convey signals from one neuron to another, helping neuronal circuits to encode memories in the brain. This process of selective strengthening is known as synaptic potentiation, and it is the favored mechanism by which the brain is thought to accomplish learning and remembering.

Yet while replay and potentiation are known to occur during waking activities, scientists have so far found no direct evidence that the synapses in replayed circuits get strengthened during sleep. This lack of evidence hardly surprises us. It is consistent with our suspicion that while the sleeper lies unaware, all that brain activity—the "replay" as well as other, seemingly random firings—might actually be *weakening* neural connections, not strengthening them.

THE PRICE OF PLASTICITY

THERE ARE MANY good reasons to propose that synapses must become weakened as well as strengthened for the brain to function properly. For one thing, strong synapses consume more energy than weak ones, and the brain does not have infinite stores of energy. In humans the brain accounts for almost 20 percent of the body's energy budget—more than any other organ by weight—and at least two thirds of that portion goes to supporting synaptic activity. Building and bolstering synapses is also a major source of cellular stress, requiring cells to synthesize and deliver components ranging from mitochondria (the cell's power plants), to synaptic vesicles (which ferry signaling molecules), to various proteins and lipids that are needed for communication across synapses.

It seems clear to us that this strain on resources is unsustainable. The brain cannot go on strengthening and maintaining revved-up synapses both day and night for the whole of an individual's lifetime. We do not doubt that learning occurs mainly through synaptic potentiation. We simply doubt that strengthening continues to happen during sleep.

In contrast, synaptic weakening during sleep would restore brain circuitry to a baseline level of strength, thereby avoiding excessive energy consumption and cellular stress. We refer to this baseline-restoring function of sleep as preserving synaptic homeostasis, and we call our overall hypothesis about the role of sleep the synaptic homeostasis hypothesis, or SHY. In principle, SHY explains the essential, universal purpose of sleep for all organisms that do it: sleep restores the brain to a state where it can learn and adapt when we are awake. The risk we take by becoming disconnected from the environment for hours at a time is the price we pay for this neural recalibration. Most generally, sleep is the price we pay for the brain's plasticity—its ability to modify its wiring in response to experience.

But how does SHY explain sleep's salutary effects on learning and memory? How can weakened synapses improve the overall retention of skills and facts? Consider that, over the course of a typical day, almost everything you experience leaves a neural trace in the brain and that the significant events, like meeting a new person or learning a piece of music on the guitar, make up just a trifling portion of that neural encoding. To improve memory, the sleeping brain must somehow distinguish the "noise" of irrelevant information from the "signal" of significant happenings.

We suggest that in sleep, the spontaneous firing of neurons in the brain activates many different circuits in many different combinations, encompassing both new memory traces and old networks of learned associations. (You get a glimpse of this neural free-for-all in dreams.) The spontaneous activity lets the brain try out which new memories fit better with stored memories of proved significance and weakens those synapses that do not fit well in the grand scheme of memory. We and other investigators are exploring possible mechanisms by which brain activity could selectively weaken synapses that encode the "noise" while preserving those that correspond to the "signal."

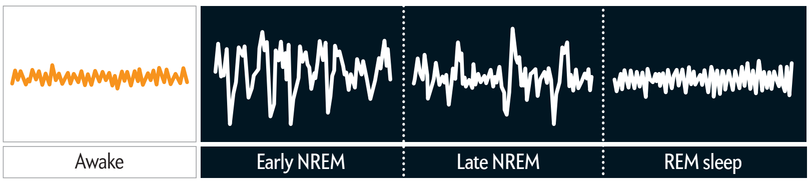
While the brain tries out these imaginary scenarios and enacts weakening

Illustrations by Jen Christiansen

POSSIBLE MECHANISM

Sleep Comes in Waves

Recordings of electrical activity in the brain show that brain waves undergo distinctive changes throughout the night as the sleeper alternates between rapid eye movement (REM) and non-REM (NREM) sleep (*graphs*). The slower waves of NREM sleep decrease in size through the course of a night—a pattern suggesting that the synapses involved in these waves get weaker. The authors propose that this weakening occurs in part because certain chemicals needed for strengthening activated synapses become much less concentrated then.



where appropriate, we had best be unaware of the surrounding environment and be incapable of acting in it; that is, we had best be asleep. Likewise, restoring synaptic homeostasis should not take place while we are awake because the events of the day would dominate the process, giving salience to them rather than to all the knowledge the brain has accumulated over a lifetime. The profound disconnection of sleep frees our brain from the tyranny of the present, creating an ideal circumstance for integrating and consolidating memories.

A WEAK CONNECTION

OUR PROPOSAL that the brain uses neuronal firing during sleep to weaken rather than strengthen synapses is supported in part by close analyses of data from a standard workhorse of sleep research: the electroencephalogram, or EEG. EEGs record patterns of electrical activity in the cerebral cortex via electrodes attached to the scalp. Decades ago EEG recordings of the sleeping brain revealed two main categories of sleep, called rapid eye movement (REM) and non-REM (NREM), that alternate throughout the night. Each has distinctive brain-wave patterns. In addition to the jittering of eyeballs underneath closed lids that gives REM sleep its name, that stage is dominated by relatively fast oscillations—quick ups and downs in the curves of the EEG readout, resembling EEG recordings of the waking state. In contrast, slow oscillations—with frequencies of about one cycle per second—are the most prominent feature of NREM sleep.

A decade ago the late Mircea Steriade of Laval University in Quebec discovered that the slow oscillations of NREM sleep arise when groups of neurons fire together for a little while (so-called on periods), then fall silent for about a fraction of a second (off periods) and then resume their synchronized firing. This was one of the fundamental discoveries in sleep research. Since then, scientists have also discovered that in birds and mammals, the slow waves are large if preceded by a long period of wakefulness and become smaller as sleep goes on.

We reasoned that if synapses are strong, neurons will synchronize their firing more, producing larger slow waves. If synapses are weak, neurons will be less synchronized and the resulting slow waves will be smaller. Results of computer simulations and experiments in humans and animals led us to conclude that the big, steep slow waves early in the night indicate that synapses have been strengthened by prior wakefulness, whereas the small, shallow slow waves early in the morning indicate that synapses have become weaker during sleep.

Direct support for the idea that synapses become weaker during sleep, and may even be pruned away, comes from studies in animals. In fruit flies, for instance, we find that sleep reverses a progressive increase in the number and size of synapses that occurs during the day, especially when the flies are exposed to stimulating environments. Synaptic spines are specialized protrusions on a neuron's signal-detecting arm. When fruit flies spend the day interacting with other flies, neurons throughout their brain sprout more synaptic spines by evening than were present in the morning.

Just as remarkably, the number of spines goes back to the baseline level by the following morning if—and only if—the flies are allowed to sleep. We saw a similar phenomenon in the cerebral cortex of adolescent mice: the number of synaptic spines tended to rise when the animals were awake and to fall when they slept. In adult rodents, the upshot is the same, although it is not the number of synaptic spines that changes with wakefulness and sleep but rather the abundance of certain spine molecules, known as AMPA receptors, that determine the strength of a synapse. When we monitored these AMPA receptors, we found that their number per synapse increases after wakefulness and decreases after sleep. More receptors make for stronger synapses; fewer mean the synapses have weakened.

Synaptic strength can be gauged directly by using an electrical probe to stimulate neural fibers in the cortex. The neurons respond with an induced electrical discharge that is larger when synapses are strong and smaller when the connections are weak. We showed that in rats, stimulated neurons fire more strongly after a few hours of wakefulness and less strongly after sleep. Marcello Massimini of the University of Milan in Italy and Reto Huber, now at the University of Zurich, performed a similar experiment in humans. Instead of an electrical probe, they turned to transcranial magnetic stimulation—a short magnetic pulse applied to the scalp—to stimulate the underlying neurons. They then recorded the strength of the cortical responses with high-density EEG. The results were clear: the longer a subject was awake, the larger the EEG responses. It took a night of sleep for cortical responses to return to the baseline.

LESS IS MORE

THE COMMON conclusion of these experiments, which we performed over two decades, is that spontaneous cortical activity in sleep does indeed weaken the synaptic connections in neural circuits, whether by damping their ability to send electrical impulses or by erasing them outright.

This process, which we call down selection, would ensure the survival of the circuits that are "fittest," either because they were activated strongly and consistently during wakefulness (say, by playing the right notes on a guitar while trying to master a new piece) or because they were better integrated with previous, older memories (as would be the case for a new word encountered in a known language). Meanwhile synapses in circuits that were only mildly enhanced during wakefulness (such as fumbled notes on the guitar) or that fit less with old memories (such as a new word presented in an unknown language) would be depressed.

Down selection would ensure that insignificant events would leave no lasting trace in our neural circuitry, whereas memories of note would be preserved. As an additional bonus, down selection would also make room for another cycle of synaptic strengthening during wakefulness. Indeed, some findings imply that among its many other benefits for learning and memory, sleep aids the subsequent acquisition of new memories (material encountered before the next bout of sleep). Quite a few studies have shown that after a night of sleep, you can learn new material much better than you can after having been awake all day. (Students, take note.)

Although we have no direct evidence for a mechanism that would produce selective weakening of activated synapses as yet, we have a notion of how synaptic weakening could occur. We suspect the slow waves of mammalian NREM sleep somehow play a role. In lab studies of rat brain tissue, nerve cells became less effective at passing signals to one another when stimulated in ways that mimic the synchronized on/off cycles of slow-wave sleep.

The chemistry of the brain also changes in NREM sleep in a way that could lead to synaptic weakening. In the awake individual, a concentrated soup of signaling chemicals, or neuromodulators—including acetylcholine, norepinephrine, dopamine, serotonin, histamine and hypocretin—bathe the brain and bias synapses toward strengthening when signals pass through them. During sleep—especially NREM sleep—the soup becomes much less concentrated. This diluted milieu of neuromodulators may bias the neural circuitry so that synapses become weakened, rather than strengthened, when signals flow across them. The process might also involve a substance called brain-derived neurotrophic factor (BDNF), which is known to promote synaptic strengthening and to be involved in memory acquisition. BDNF levels are high in neurons during wakefulness and minimal during sleep.

LOCAL SLEEP

REGARDLESS of specific mechanisms and selective processes, the evidence is strong in several species that overall synaptic strength goes up during wakefulness and down during sleep: the core prediction of SHY. We can test SHY further by examining some of its intriguing corollaries.

For example, if the hypothesis is correct, then the more plasticity a part of the brain undergoes during wakefulness, the more that part should need to sleep. "Sleep need" can, in turn, be indicated by an increase in the size and duration of NREM slow waves. To explore this prediction, we asked human subjects to learn a novel task: how to reach a target on a computer screen while the cursor (controlled by a mouse) is systematically rotated. The part of the brain that engages in this kind of learning is the right parietal cortex. Sure enough, when our subjects slept, the slow waves over their right parietal cortex were larger, relative to waves from the same area on the night before learning occurred. These large waves did flatten out in the course of the night, as such oscillations do. But those large, localized waves at the start of the night tell us that particular part of the brain had been exhausted by the task we assigned.

Many other experiments by the two of us and others have since confirmed that learning, and more generally the activation of synapses in circuits, produces a local increase in sleep need. Recently we have even found that prolonged or intense use of certain circuits can make local groups of neurons "fall asleep" even though the rest of the brain (and the organism itself) remains awake. Thus, if a rat stays awake longer than usual, some cortical neurons show brief periods of silence that are basically indistinguishable from the off periods observed during slow-wave sleep. Meanwhile the rat is running around, its eyes open, tending to its business, as any awake rat would do.

This phenomenon is called local sleep, and it is attracting scrutiny from other investigators. Our latest studies indicate that localized off periods also occur in the brains of sleep-deprived humans and that those periods become more frequent after intense learning. It seems that when we have been awake for too long or have overexerted certain circuits, small chunks of the brain may take quick naps without giving notice. One wonders how many errors of judgment, silly mistakes, irritable responses and foul moods result from local sleep in the brains of exhausted people who believe they are fully awake and in complete control.

SHY also predicts that sleep is especially important in childhood and adolescence, times of concentrated learning and of intense synaptic remodeling, as many studies have shown. In youth, synapses are formed, strengthened and pruned at an explosive rate never approached in adulthood. It makes sense that down selection during sleep would be crucial to minimize the energy costs of this frenzied synaptic remodeling and to favor the survival of adaptive neural circuits in these stages of life. One can only wonder what happens when sleep is disrupted or insufficient during critical periods in development. Might the deficit corrupt the proper refinement of neural circuits? In that case, the effect of sleep loss would not merely be occasional forgetfulness or misjudgment but a lasting change in the way the brain is wired.

We look forward to testing SHY's predictions and exploring its implications further. For example, we hope to discover whether sleep deprivation during neural development leads to changes in the organization of brain circuitry. We would also like to learn more about the effect of sleep on deep-brain areas, such as the thalamus, cerebellum, hypothalamus and brain stem, and about the role of REM sleep in synaptic homeostasis. Perhaps we would then learn if sleep is indeed the price of waking plasticity, a price that every brain and every neuron must pay. SA

MORE TO EXPLORE

Is Sleep Essential? Chiara Cirelli and Giulio Tononi in *PLOS Biology,* Vol. 6, No. 8, pages 1605–1611; August 2008.

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Local Sleep in Awake Rats. Vladyslav V. Vyazovskiy, Umberto Olcese, Erin C. Hanlon, Yuval Nir, Chiara Cirelli and Giulio Tononi in *Nature,* Vol. 472, pages 443–447; April 28, 2011.

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SCIENTIFIC AMERICAN ONLINE
Watch author Giulio Tononi speak about the function of sleep at **ScientificAmerican.com/aug2013/sleep**

QUANTUM PHYSICS

what is

real?

Physicists speak of the world as being made of particles and force fields, but it is not at all clear what particles and force fields actually are in the quantum realm. The world may instead consist of bundles of properties, such as color and shape

By Meinard Kuhlmann

Photographs by Travis Rathbone

Meinard Kuhlmann, a philosophy professor at Bielefeld University in Germany, received dual degrees in physics and in philosophy and has worked at the universities of Oxford, Chicago and Pittsburgh. As a student, he had an inquisitive reputation. "I would ask a lot of questions just for fun and because they produced an entertaining confusion," he says.

Physicists routinely describe the universe as being made of tiny subatomic particles that push and pull on one another by means of force fields. They call their subject "particle physics" and their instruments "particle accelerators." They hew to a Lego-like model of the world. But this view sweeps a little-known fact under the rug: the particle interpretation of quantum physics, as well as the field interpretation, stretches our conventional notions of "particle" and "field" to such an extent that ever more people think the world might be made of something else entirely.

The problem is not that physicists lack a valid theory of the subatomic realm. They do have one: it is called quantum field theory. Theorists developed it between the late 1920s and early 1950s by merging the earlier theory of quantum mechanics with Einstein's special theory of relativity. Quantum field theory provides the conceptual underpinnings of the Standard Model of particle physics, which describes the fundamental building blocks of matter and their interactions in one common framework. In terms of empirical precision, it is the most successful theory in the history of science. Physicists use it every day to calculate the aftermath of particle collisions, the synthesis of matter in the big bang, the extreme conditions inside atomic nuclei, and much besides.

So it may come as a surprise that physicists are not even sure what the theory says—what its "ontology," or basic physical picture, is. This confusion is separate from the much discussed mysteries of quantum mechanics, such as whether a cat in a sealed box can be both alive and dead at the same time. The unsettled interpretation of quantum field theory is hobbling progress toward probing whatever physics lies beyond the Standard Model, such as string theory. It is perilous to formulate a new theory when we do not understand the theory we already have.

At first glance, the content of the Standard Model appears obvious. It consists, first, of groups of elementary particles, such as quarks and electrons, and, second, of four types of force fields, which mediate the interactions among those particles. This picture appears on classroom walls and in *Scientific American* articles. However compelling it might appear, it is not at all satisfactory.

For starters, the two categories blur together. Quantum field theory assigns a field to each type of elementary particle, so there is an electron field as surely as there is an electron. At the same time, the force fields are quantized rather than continuous, which gives rise to particles such as the photon. So the distinction between particles and fields appears to be artificial, and physicists often speak as if one or the other is more fundamental. Debate has swirled over this point—over whether quantum field theory is ultimately about particles or about fields. It started as a battle of titans, with eminent physicists and philosophers on both sides. Even today both concepts are still in use for illustrative purposes, although most physicists would admit that the classical conceptions do not match what the theory says. If the mental images conjured up by the words "particle" and "field" do not match what the theory says, physicists and philosophers must figure out what to put in their place.

With the two standard, classical options gridlocked, some philosophers of physics have been formulating more radical alternatives. They suggest that the most basic constituents of the material world are intangible entities such as relations or properties. One particularly radical idea is that everything can be reduced to intangibles alone, without any reference to individual things. It is a counterintuitive and revolutionary idea, but some argue that physics is forcing it on us.

THE TROUBLE WITH PARTICLES

WHEN MOST PEOPLE, including experts, think of subatomic reality, they imagine particles that behave like little billiard balls rebounding off one another. But this notion of particles is a holdover of a worldview that dates to the ancient Greek atomists and reached its pinnacle in the theories of Isaac Newton. Several overlapping lines of thought make it clear that the core units of quantum field theory do not behave like billiard balls at all.

First, the classical concept of a particle implies something that exists in a certain location. But the "particles" of quantum field theory do not have well-defined locations: a particle inside

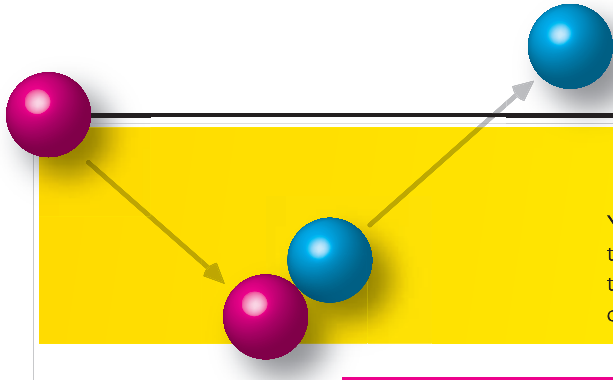
IN BRIEF

It stands to reason that particle physics is about particles, and most people have a mental image of little billiard balls caroming around space. Yet the concept of "particle" falls apart on closer inspection.

Many physicists think that particles are not things at all but excitations in a quantum field, the modern successor of classical fields such as the magnetic field. But fields, too, are paradoxical.

If neither particles nor fields are fundamental, then what is? Some researchers think that the world, at root, does not consist of material things but of relations or of properties, such as mass, charge and spin.

PRECEDING PAGES: PROP STYLING BY SARAH GUIDO



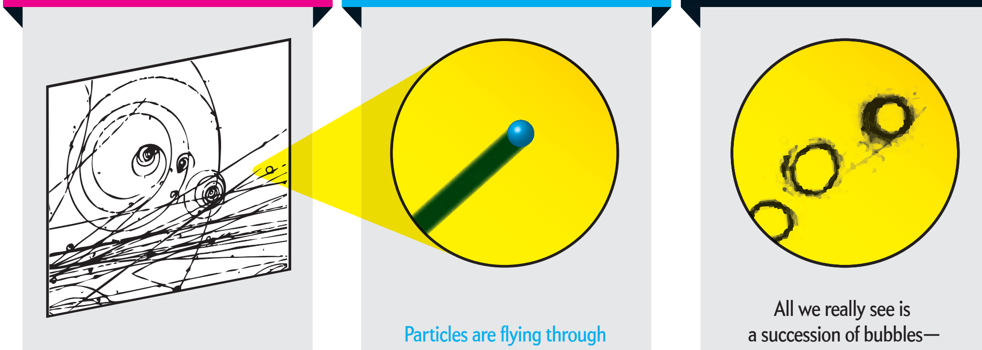
Not Just Tiny Billiard Balls

You would be forgiven for thinking that particle physics is about particles. It turns out, though, that the "particles" described by quantum theory do not fit the usual sense of the term, which refers to discrete, localized building blocks of matter. They lack, for instance, the four classical attributes listed below.

What we see/calculate/do	What we infer	Why it's wrong

Particles Are Localized

By definition, a particle is something with a specific position, which changes in time as it moves. But quantum theory, as usually understood, does not allow anything to have such a trajectory. Although instruments such as bubble chambers reveal tracks, it is fallacious to infer objects that move through space like balls. The tracks are just a series of events.



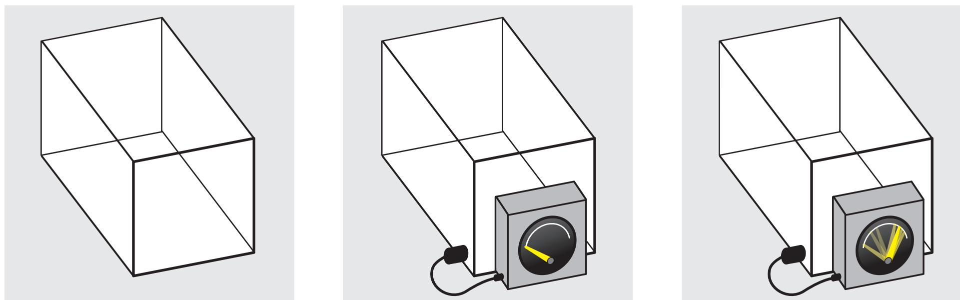
Tracks in a bubble chamber

Particles are flying through the chamber and leaving tracks

All we really see is a succession of bubbles— it's a mistake to link them together

In the Absence of Particles, Nothing Can Happen

If particles make up matter, then a vacuum, a state of zero particles, should show no activity. But quantum theory predicts that a Geiger counter or similar instrument placed somewhere within the vacuum still registers the presence of matter. Therefore, matter cannot consist of things typically evoked by term "particle."



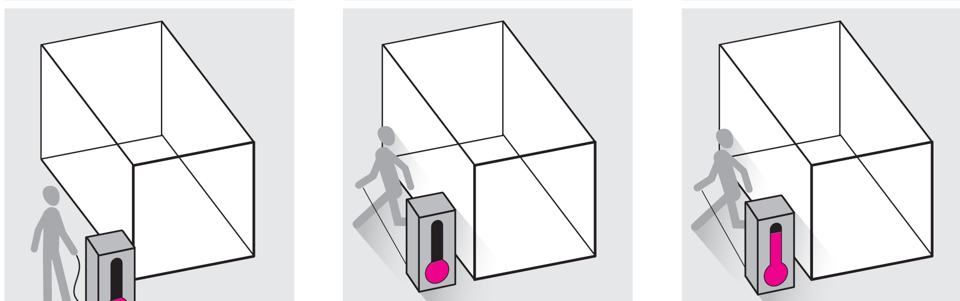
A field in its vacuum state

A measurement probe such as a Geiger counter will detect nothing

A Geiger counter will click

A Particle Exists, or It Doesn't

To determine whether something is real, physicists use a simple test: all observers should be able to agree on its existence. The "particles" that physicists detect in nature fail this test. If an observer at rest sees a cold vacuum, an accelerating observer sees a warm gas of particles, suggesting that the particles are some kind of mirage.



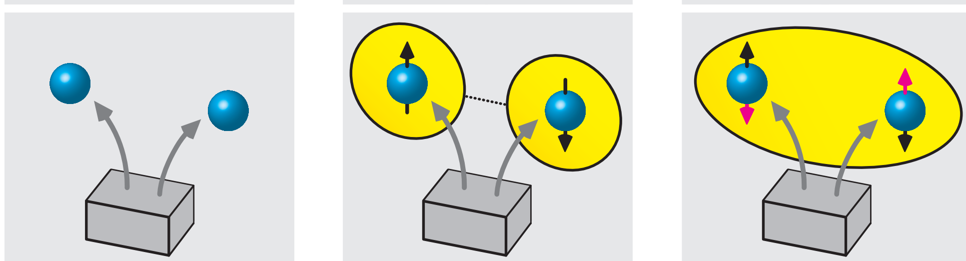
An observer sees a cold vacuum

Another observer will also see a cold vacuum

An accelerating observer sees a warm gas of particles

Particles Have Specific Properties

Particles are supposed to have energy, momentum, and so on. But quantum physics allows objects to become entangled, operating as a unit despite no obvious material links among them. In that case, the putative particles no longer have definite properties; only the system as a whole does.



Produce a pair of entangled particles

Each particle has a definite spin

Only the system as a whole has a definite spin

Illustrations by Jen Christiansen

your body is not strictly inside your body. An observer attempting to measure its position has a small but nonzero probability of detecting it in the most remote places of the universe. This contradiction was evident in the earliest formulations of quantum mechanics but became worse when theorists merged quantum mechanics with relativity theory. Relativistic quantum particles are extremely slippery; they do not reside in any specific region of the universe at all.

Second, let us suppose you had a particle localized in your kitchen. Your friend, looking at your house from a passing car, might see the particle spread out over the entire universe. What is localized for you is delocalized for your friend. Not only does the location of the particle depend on your point of view, so does the fact that the particle *has* a location. In this case, it does not make sense to assume localized particles as the basic entities.

Third, even if you give up trying to pinpoint particles and simply count them, you are in trouble. Suppose you want to know the number of particles in your house. You go around the house and find three particles in the dining room, five under the bed, eight in a kitchen cabinet, and so on. Now add them up. To your dismay, the sum will *not* be the total number of particles. That number in quantum field theory is a property of the house as a whole; to determine it, you would have to do the impossible and measure the whole house in one go, rather than room by room.

An extreme case of particles' being unpinpointable is the vacuum, which has paradoxical properties in quantum field theory. You can have an overall vacuum—by definition, a zero-particle state—while at the same time you observe something very different from a vacuum in any finite region. In other words, your house can be totally empty even though you find particles all over the place. If the fire department asks you whether anyone is still inside a burning house and you say no, the firefighters will question your sanity when they discover people huddled in every room.

Another striking feature of the vacuum in quantum field theory is known as the Unruh effect. An astronaut at rest may think he or she is in a vacuum, whereas an astronaut in an accelerating spaceship will feel immersed in a thermal bath of innumerable particles. This discrepancy between viewpoints also occurs at the perimeter of black holes and leads to paradoxical conclusions about the fate of infalling matter [see "Black Holes and the Information Paradox," by Leonard Susskind; Scientific American, April 1997]. If a vacuum filled with particles sounds absurd, that is because the classic notion of a particle is misleading us; what the theory is describing must be something else. If the number of particles is observer-dependent, then it seems incoherent to assume that particles are basic. We can accept many features to be observer-dependent but not the very fact of how many basic building blocks there are.

Finally, the theory dictates that particles can lose their individuality. In the puzzling phenomenon of quantum entanglement, particles can become assimilated into a larger system and give up the properties that distinguish them from one another. The presumptive particles share not only innate features such as mass and charge but also spatial and temporal properties such as the range of positions over which they might be found. When particles are entangled, an observer has no way of telling one from the other. At that point, do you really have *two* objects anymore?

A theorist might simply decree that our would-be two particles are two distinct individuals. Philosophers call this diktat "primitive thisness." By definition, this thisness is unobservable. Most physicists and philosophers are very skeptical of such ad hoc moves. Rather, it seems, you no longer have two particles anymore. The entangled system behaves as an indivisible whole, and the notion of a part, let alone a particle, loses its meaning.

These theoretical problems with particles fly in the face of experience. What do "particle detectors" detect if not particles? The answer is that particles are always an inference. All a detector registers is a large number of separate excitations of the sensor material. We run into trouble when we connect the dots and infer the existence of particles having trajectories that can be traced in time. (Caveat: Some minority interpretations of quantum physics do think in terms of well-defined trajectories. But they suffer from their own difficulties, and I stick to the standard view [see "Bohm's Alternative to Quantum Mechanics," by David Z Albert; Scientific American, May 1994].)

So let us take stock. We think of particles as tiny billiard balls, but the things that modern physicists call "particles" are nothing like that. According to quantum field theory, objects cannot be localized in any finite region of space, no matter how large or fuzzy it is. Moreover, the number of the putative particles depends on the state of motion of the observer. All these results taken together sound the death knell for the idea that nature is composed of anything akin to ball-like particles.

On the basis of these and other insights, one must conclude that "particle physics" is a misnomer: despite the fact that physicists keep talking about particles, there are no such things. One may adopt the phrase "quantum particle," but what justifies the use of the word "particle" if almost nothing of the classical notion of particles has survived? It is better to bite the bullet and abandon the concept altogether. Some take these difficulties as indirect evidence for a pure field interpretation of quantum field theory. By this reasoning, particles are ripples in a field that fills space like an invisible fluid. Yet as we will see now, quantum field theory cannot be readily interpreted in terms of fields, either.

THE TROUBLE WITH FIELDS

The name "quantum field theory" naturally connotes a theory that deals with quantum versions of classical fields, such as the electric and magnetic fields. But what *is* a "quantum version"? The term "field" conjures up magnetic fields that cause iron filings to align themselves around a bar magnet and electric fields that cause hair to stand up on end, but a quantum field is so different from a classical one that even theoretical physicists admit they can barely visualize it.

Classically, a field assigns a physical quantity, such as temperature or electric field strength, to each point in spacetime. A quantum field instead assigns abstract mathematical entities, which represent the type of measurements you could conduct, rather than the result you would obtain. Some mathematical constructions in the theory do represent physical values, but these cannot be assigned to points in spacetime, only to smeared-out regions.

Historically, physicists developed quantum field theory by "quantizing" classical field theory. In this procedure, theorists go through an equation and replace physical values with "operators," which are mathematical operations such as differentiation or taking the square root, and some operators can correspond to specific physical processes such as the emission and absorption of light. Operators place a layer of abstraction between the theory and reality. A classical field is like a weather map that shows the temperature in various cities. The quantum version is like a weather map that does not show you “40 degrees,” but “$\sqrt{\ }$.” To obtain an actual temperature value, you would need to go through an extra step of applying the operator to another mathematical entity, known as a state vector, which represents the configuration of the system in question.

On some level, this peculiarity of quantum fields does not seem surprising. Quantum mechanics—the theory on which quantum field theory is based—does not traffic in determinate values either but only in probabilities. Ontologically, though, the situation seems weirder in quantum field theory because the supposedly fundamental entities, the quantum fields, do not even specify any probabilities; for that, they must be combined with the state vector.

The need to apply the quantum field to the state vector makes the theory very difficult to interpret, to translate into something physical you can imagine and manipulate in your mind. The state vector is holistic; it describes the system as a whole and does not refer to any particular location. Its role undermines the defining feature of fields, which is that they are spread out over spacetime. A classical field lets you envision phenomena such as light as propagation of waves across space. The quantum field takes away this picture and leaves us at a loss to say how the world works.

Clearly, then, the standard picture of elementary particles and mediating force fields is not a satisfactory ontology of the physical world. It is not at all clear what a particle or field even is. A common response is that particles and fields should be seen as complementary aspects of reality. But that characterization does not help, because neither of these conceptions works even in those cases where we are supposed to see one or the other aspect in purity. Fortunately, the particle and field views do not exhaust the possible ontologies for quantum field theory.

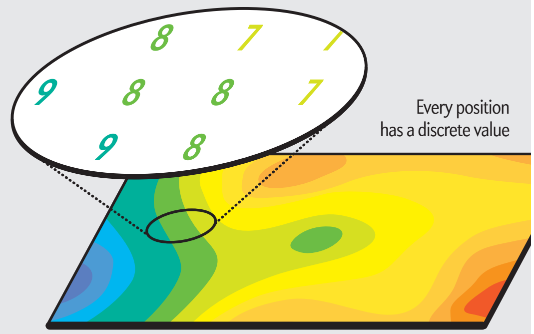
FAILURES OF FIELDS

No Field of Dreams

Physicists call their leading theory of matter “quantum field theory.” That sounds like a theory of fields. Yet the fields supposedly described by the theory are not what physicists classically understand by the term “field.”

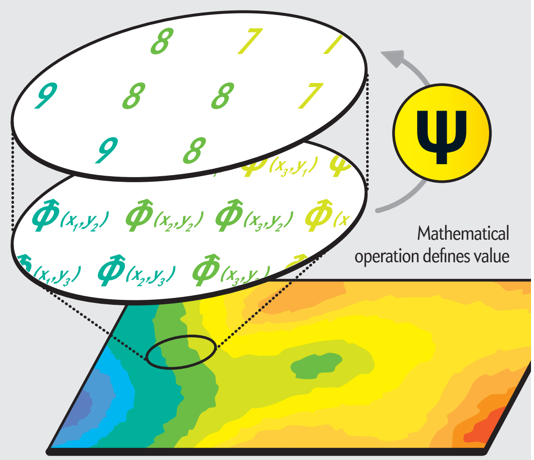
Classical Field

By definition, a field is an almost fluid-like substance that pervades space. Every point in it has a measurable state. An example is the electric field. The amplitude of the field is greater around wires, electrically charged objects, and so on. If you place a charged particle somewhere in space, the amplitude determines what force the particle will feel and how fast it will be accelerated. The field also defines the direction in which it will be accelerated (*not shown*).



Quantum Field

Fields described by quantum theory do not fit this definition. A point in space does not take on a specific physical quantity, merely a spectrum of possible quantities. The value that is actually chosen depends on a separate mathematical construct known as the state vector, which is not assigned to any specific location; it spans all of space.



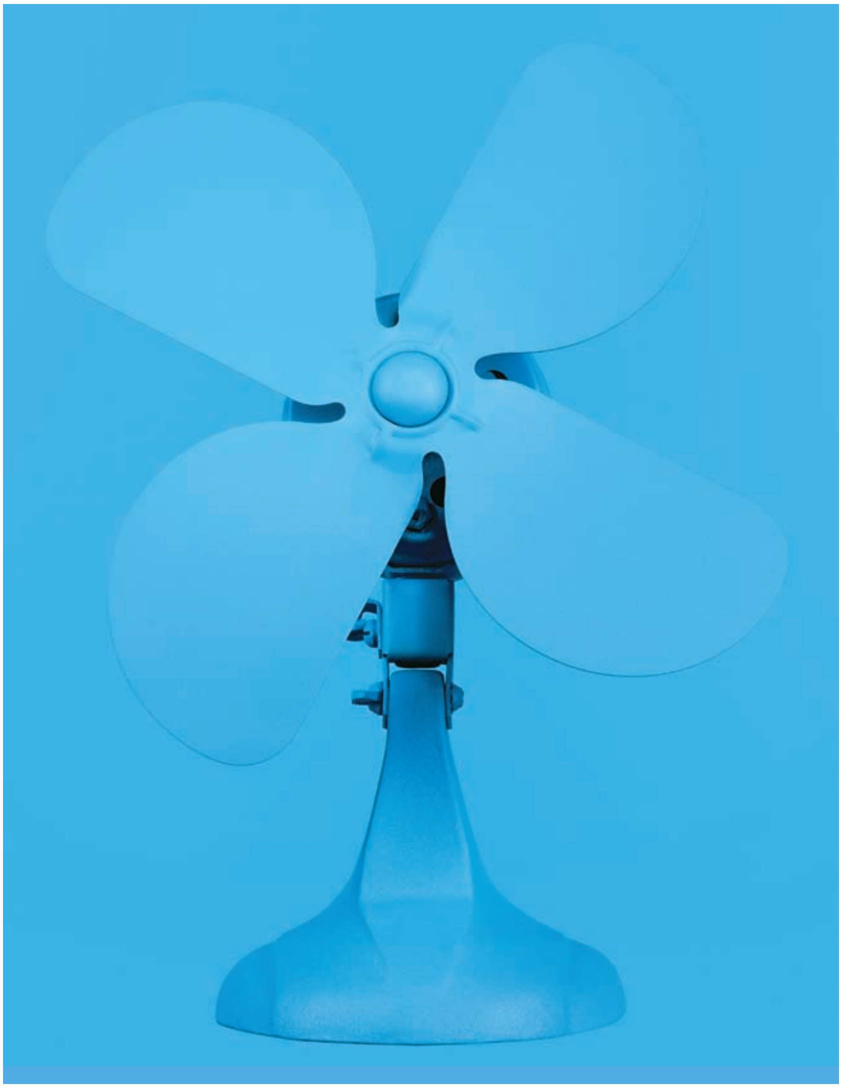
STRUCTURES TO THE RESCUE?

A GROWING NUMBER of people think that what really matters are not things but the relations in which those things stand. Such a view breaks with traditional atomistic or pointillist conceptions of the material world in a more radical way than even the severest modifications of particle and field ontologies could do.

Initially this position, known as structural realism, came in a fairly moderate version known as epistemic structural realism. It runs as follows: We may never know the real natures of things but only how they are related to one another. Take the example of mass. Do you ever see mass itself? No. You see only what it means for other entities or, concretely, how one massive body is related to another massive body through the local gravitational field. The structure of the world, reflecting how things are interrelated, is the most enduring part of physics theories. New theories may overturn our conception of the basic building blocks of the world, but they tend to preserve the structures. That is how scientists can make progress.

Now the following question arises: What is the reason that we can know only the relations among things and not the things themselves? The straightforward answer is that relations are all there is. This leap makes structural realism a more radical proposition, called ontic structural realism.

The myriad symmetries of modern physics lend support to



the things that are related. In a subway network, for example, it is crucial to know how the different stations are connected. In London, St. Paul's is directly connected to Holborn, whereas from Blackfriars you need to change lines at least once, even though Blackfriars is closer to Holborn than St. Paul's. It is the structure of the connections that matters primarily. The fact that Blackfriars Tube station has recently been renovated into a nice new station does not matter to someone trying to navigate the system.

Other examples of structures that take priority over their material realization are the World Wide Web, the brain's neural network and the genome. All of them still function even when individual computers, cells, atoms and people die. These examples are loose analogies, although they are close in spirit to the technical arguments that apply to quantum field theory.

A closely related line of reasoning exploits quantum entanglement to make the case that structures are the basis of reality. The entanglement of two quantum particles is a holistic effect. All the intrinsic properties of the two particles, such as electrical charge, together with all their extrinsic properties, such as position, still do not determine the state of the two-particle system. The whole is more than the sum of its parts. The atomistic picture of the world, in which everything is determined by the properties of the most elementary building blocks and how they are related in spacetime, breaks down. Instead of considering particles primary and entanglement secondary, perhaps we should think about it the other way round.

You may find it is strange that there could be relations without relata—without any objects that stand in that relation. It sounds like having a marriage without spouses. You are not alone. Many physicists and philosophers find it bizarre, too, thinking it impossible to get solid objects merely on the basis of relations. Some proponents of ontic structural realism try to compromise. They do not deny objects exist; they merely claim that relations, or structures, are ontologically primary. In other words, objects do not have intrinsic properties, only properties that come from their relations with other objects. But this position seems wishy-washy. Anyone would agree that objects have relations. The only interesting and new position would be that everything emerges purely on the basis of relations. All in all, structural realism is a provocative idea but needs to be developed further before we will know whether it can rescue us from our interpretive trouble.

ontic structural realism. In quantum mechanics as well as in Einstein's theory of gravitation, certain changes in the configuration of the world—known as symmetry transformations—have no empirical consequences. These transformations exchange the individual things that make up the world but leave their relations the same. By analogy, consider a mirror-symmetric face. A mirror swaps the left eye for the right eye, the left nostril for the right, and so on. Yet all the relative positions of facial features remain. Those relations are what truly define a face, whereas labels such as "left" and "right" depend on your vantage point. The things we have been calling "particles" and "fields" possess more abstract symmetries, but the idea is the same.

By the principle of Occam's razor, physicists and philosophers prefer ideas that can explain the same phenomena with the fewest assumptions. In this case, you can construct a perfectly valid theory by positing the existence of specific relations without additionally assuming individual things. So proponents of ontic structural realism say we might as well dispense with things and assume that the world is made of structures, or nets of relations.

In everyday life we encounter many situations where only relations count and where it would be distracting to describe

BUNDLES OF PROPERTIES

A SECOND ALTERNATIVE for the meaning of quantum field theory starts from a simple insight. Although the particle and field interpretations are traditionally considered to be radically differ-

PROP STYLING BY SARAH GUIDO

ent from each other, they have something crucial in common. Both assume that the fundamental items of the material world are persistent individual entities to which properties can be ascribed. These entities are either particles or, in the case of field theory, spacetime points. Many philosophers, including me, think this division into objects and properties may be the deep reason why the particle and field approaches both run into difficulties. We think it would be better to view properties as the one and only fundamental category.

Traditionally, people assume that properties are "universals"—in other words, they belong to an abstract, general category. They are always possessed by particular things; they cannot exist independently. (To be sure, Plato did think of them as existing independently but only in some higher realm, not the world that exists in space and time.) For instance, when you think of red, you usually think of particular red things and not of some freely floating item called "redness." But you could invert this way of thinking. You can regard properties as having an existence, independently of objects that possess them. Properties may be what philosophers call "particulars"—concrete, individual entities. What we commonly call a thing may be just a bundle of properties: color, shape, consistency, and so on.

Because this conception of properties as particulars rather than universals differs from the traditional view, philosophers have introduced a new term to describe them: "tropes." It sounds a bit funny, and unfortunately the term brings inappropriate connotations with it, but it is established by now.

Construing things as bundles of properties is not how we usually conceptualize the world, but it becomes less mysterious if we try to unlearn how we usually think about the world and set ourselves back to the very first years of life. As infants, when we see and experience a ball for the first time, we do not actually perceive a ball, strictly speaking. What we perceive is a round shape, some shade of red, with a certain elastic touch. Only later we do associate this bundle of perceptions with a coherent object of a certain kind—namely, a ball. Next time we see a ball, we essentially say, "Look, a ball," and forget how much conceptual apparatus is involved in this seemingly immediate perception.

In trope ontology, we return to the direct perceptions of infancy. Out there in the world, things are nothing but bundles of properties. It is not that we first have a ball and then attach properties to it. Rather we have properties and call it a ball. There is nothing to a ball but its properties.

Applying this idea to quantum field theory, what we call an electron is in fact a bundle of various properties or tropes: three fixed, essential properties (mass, charge and spin), as well as numerous changing, nonessential properties (position and velocity). This trope conception helps to make sense of the theory. For instance, the theory predicts that elementary particles can pop in and out of existence quickly. The behavior of the vacuum in quantum field theory is particularly mind-boggling: the average value of the number of particles is zero, yet the vacuum seethes with activity. Countless processes take place all the time, involving the creation and subsequent destruction of all kinds of particles.

In a particle ontology, this activity is paradoxical. If particles are fundamental, then how can they materialize? What do they materialize out of? In the trope ontology, the situation is natural. The vacuum, though empty of particles, contains properties. A particle is what you get when those properties bundle themselves together in a certain way.

PHYSICS AND METAPHYSICS

HOW CAN THERE BE so much fundamental controversy about a theory that is as empirically successful as quantum field theory? The answer is straightforward. Although the theory tells us what we can measure, it speaks in riddles when it comes to the nature of whatever entities give rise to our observations. The theory accounts for our observations in terms of quarks, muons, photons and sundry quantum fields, but it does not tell us what a photon or a quantum field really is. And it does not need to, because theories of physics can be empirically valid largely without settling such metaphysical questions.

For many physicists, that is enough. They adopt a so-called instrumentalist attitude: they deny that scientific theories are meant to represent the world in the first place. For them, theories are only instruments for making experimental predictions. Still, most scientists have the strong intuition that their theories do depict at least some aspects of nature as it is before we make a measurement. After all, why else do science, if not to understand the world?

Acquiring a comprehensive picture of the physical world requires the combination of physics with philosophy. The two disciplines are complementary. Metaphysics supplies various competing frameworks for the ontology of the material world, although beyond questions of internal consistency, it cannot decide among them. Physics, for its part, lacks a coherent account of fundamental issues, such as the definition of objects, the role of individuality, the status of properties, the relation of things and properties, and the significance of space and time.

The union of the two disciplines is especially important at times when physicists find themselves revisiting the very foundations of their subject. Metaphysical thinking guided Isaac Newton and Albert Einstein, and it is influencing many of those who are trying to unify quantum field theory with Einstein's theory of gravitation. Philosophers have written libraries full of books and papers about quantum mechanics and gravity theory, whereas we are only beginning to explore the reality embodied in quantum field theory. The alternatives to the standard particle and field views that we are developing may inspire physicists in their struggle to achieve the grand unification. SA

MORE TO EXPLORE

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What is a field? For a pithy video explanation, see **ScientificAmerican.com/aug2013/field**


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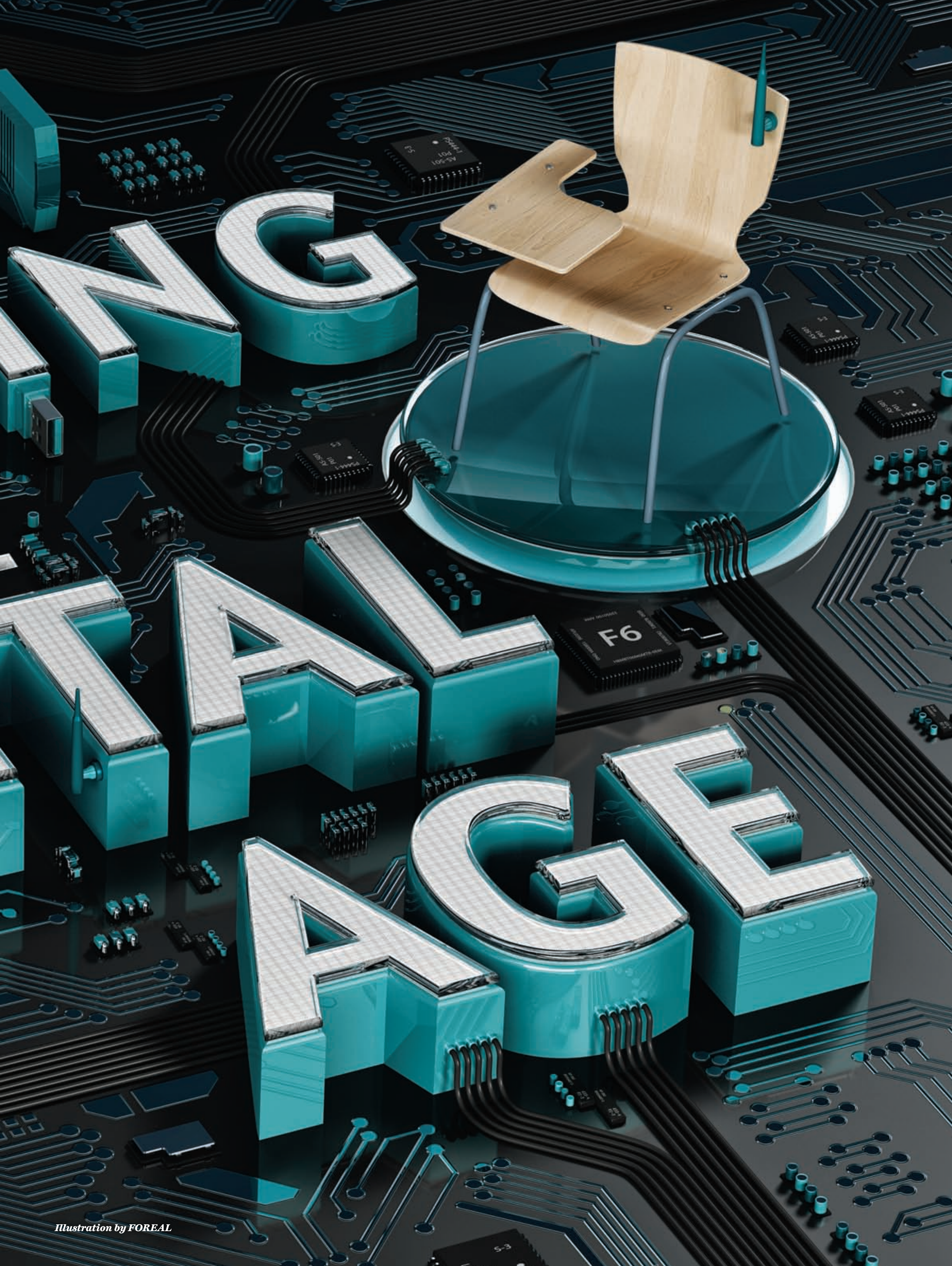


Illustration by FOREAL

IN BRIEF

Data analytics and streaming video, among other technologies, are filtering from the consumer marketplace into college and K–12 classrooms.

Massive open online courses (MOOCs) deliver free university classes to remote regions.

Adaptive learning platforms closely track student progress, tailor content to individual abilities and predict how a student will perform. But critics caution we must invest as much in great teachers as in technology.

INTRODUCTION

BIG DATA GOES TO SCHOOL

Technology is remaking every aspect of education, bringing top-notch courses to the world's poorest citizens and reshaping the way all students learn

Classrooms haven't changed much in the past few centuries. Students attend class, take notes and do their homework. The teacher lectures and once in a while administers a test. Students get their grades and move on to the next topic. By and large, students—especially the most disadvantaged ones—attend the school or university closest to their home, regardless of its quality.

These routines are starting to change. In a small but growing number of schools, students watch lectures online and come to class prepared to tackle assignments and collaborate with teachers and peers. They interact with computer programs that allow them to work at their own pace, regardless of what the rest of the class is doing. Teachers rely on those same programs to grade tests and essays, allowing them to closely track more students at once. And local schools are no longer a pupil's only option. Start-ups and nonprofits make high-quality courses available online to anyone with an Internet connection.

What is driving this digital revolution? One factor is that schools and universities are under greater pressure than ever before. More and more

MITCH PAYNE (*photograph*)

Illustration by Kyle Bean

students are pursuing higher levels of education at a time when budget-strapped principals and universities cannot hire the staff they need. At the same time, governments and institutions (prodded by employers) are raising standards for what students should know at every stage of school.

Many see technology as a solution. But skeptics think it improves little on what teachers can do and poses a threat to student privacy.

In this special section, Scientific American explores the frontiers of the new digital age in education and what it means for parents, students, teachers and society. —*The Editors*

Read a special report on digital education from *Scientific American* and *Nature* at **ScientificAmerican.com/digital-education**

BEATING THE ODDS: Online courses facilitated by on-site teachers are helping more Rwandans go to college.

MOOCs

HYPE AND HOPE

An inside look at a daring global experiment: using freely available online courses to bring top-tier instruction to the neediest parts of the planet

By Jeffrey Bartholet

Tujiza Uwituze worked hard and ranked near the top of her class in her Rwandan secondary school, but her education was poor by international standards. She had instructors who made her memorize and regurgitate information, and the school she attended had no computers for her to use. As a result, Uwituze's English is imperfect, and her computer skills are weak. She lives with a great-uncle in Kigali and has $75 in savings. Despite hard work and an intense desire to succeed, her dreams are out of reach—or might be if not for an innovative project that could radically change her life.

The goal of the experiment, called Kepler and conducted by a small nonprofit called Generation Rwanda, is to use massive open online courses (MOOCs) to deliver a top-tier education to young Rwandans who were born around the time of the 1994 genocide. The first test began in March with a "prepilot" class called Critical Thinking in Global Challenges, an online offering from the University of Edinburgh in Scotland. A dozen students viewed video lectures downloaded from a MOOC platform and attended small seminars and coaching sessions in a Kigali classroom with an on-site teaching fellow, a form of education called blended learning.

For a student like Uwituze, who was an infant during the slaughter by Hutus of some 800,000 Tutsis and their Hutu sympathizers in 1994, this was an extraordinary opportunity. Her family fled during the genocide: first to Burundi, then to Tanzania, then to Kenya. "We lost our money, our house, everything," she says. Schooling was all that Uwituze really had after years on the run. She returned to Rwanda at the age of 14 and graduated from secondary school last November. The annual tuition at Rwandan public universities is about $1,500 a year for a sub-

Photographs by Jonathan Torgovnik

REMOTE ACCESS: Tujiza Uwituze, with her mother in Kigali, hopes to earn a degree in finance, mostly through online courses.

standard education, which is more than Uwituze's family can afford. Her mother is jobless, and Uwituze has three younger siblings who look to her for support. When she was turned down by an organization that helps aspiring Rwandan students get scholarships at American universities, an official from that group suggested she join Kepler. She became one of 15 students invited to attend the prepilot course to test the MOOC format. She then applied to be accepted into a larger class, which will be enrolled in a full MOOC curriculum in the fall.

Kepler received 2,696 applications for just 50 slots in the fall program. Six hundred students were invited to take an exam in April, of which 200, including Uwituze, made it to a final round of cuts. Those 200 were interviewed in person and took part in group activities observed by Kepler staff to gauge personality traits such as leadership qualities, ability to work well with others and problem-solving skills. The aim was to put together a class that combined a range of personality types: outgoing and shy, funny and earnest, creative and conscientious. The stakes were high. Jean Aime Mutabazi did not make the first cut for the fall session and felt adrift. Most of his male relatives, including his father, were killed in the genocide. He lives with his mother, who has a mangled leg and sells charcoal from a cement hutch to earn a living. "Can you imagine what it's like when you have a problem, and there is no one to turn to for help?" Mutabazi asks. "Education is a kind of magic power that can open any door in the world. If you are educated, you can control the situation you are living in."

Uwituze made the final cut. She originally wanted to be an airline pilot but now considers that beyond reach, so she has settled on banking as a possible career. She will be able to study business and finance through Kepler. "Education is the only way I can survive," she says, "the only way I can take care of my sisters, who need me." Those accepted to the fall session will take online classes from leading universities for free—with support and mentoring from American teaching fellows in Kigali—and will also have their living expenses paid for. Generation Rwanda's executive director Jamie Hodari estimates that after an initial outlay of $100,000 for curriculum design and evaluation, the annual per-student tuition costs to his organization, including laptops and teachers' salaries, will be around $2,000. He hopes to bring that down over time to $1,000. Initially students will be on one track: toward an associate of arts degree in general studies, with a concentration in business, from Southern New Hampshire University, which has a cutting-edge program that awards degrees based on proved competencies, not the number of hours spent in a classroom. After associate degrees are completed in the second year, Kepler plans to offer bachelor's degrees in business administration, computer science and perhaps engineering from a variety of institutions.

Uwituze has questions about the online approach, including

PERSONAL TOUCH: Teacher Christine Yarng supplements online courses by meeting with students in person.

35%

Share of pre-K–12 teachers who have access to a tablet or e-reader in the classroom

DATA SOURCE: PBS LEARNINGMEDIA

Massively Personal

How thousands of online students can get the effect of one-on-one tutoring

By Peter Norvig

Educators have known for 30 years that students perform better when given one-on-one tutoring and mastery learning—working on a subject until it is mastered, not just until a test is scheduled. Success also requires motivation, whether from an inner drive or from parents, mentors or peers.

Will the rise of massive open online courses (MOOCs) quash these success factors? Not at all. In fact, digital tools offer our best path to cost-effective, personalized learning.

I know because I have taught both ways. For years Sebastian Thrun and I have given artificial-intelligence courses at Stanford University and other schools; we lectured, assigned homework and gave everyone the same exam at the same time. Each semester just 5 to 10 percent of students regularly engaged in deep discussions in class or office hours; the rest were more passive. We felt there had to be a better way.

So, in the fall of 2011, we tried something new. In addition to our traditional classroom, we created a free online course open to anyone. On our first try, we attracted a city's worth of participants—about 100,000 engaged with the course, and 23,000 finished.

Inspired by Nobel laureate Herbert Simon's comment that "learning results from what the student does and thinks and only from what the student does and thinks," we created a course centered on the students *doing things* and getting frequent feedback. Our "lectures" were short (two- to six-minute) videos designed to prime the attendees for doing the next exercise. Some problems required the application of mathematical techniques described in the videos. Others were open-ended questions that gave students a chance to think on their own and then to hash out ideas in online discussion forums.

Our scheme to help make learning happen actively, rather than passively, created many benefits akin to tutoring—and helped to increase motivation. First, as shown in a 2013 study by Karl K. Szpunar, Novall Y. Khan and Daniel L. Schacter in the *Proceedings of the National Academy of Sciences USA,* frequent interactions keep attention from wandering. Second, as William B. Wood and Kimberly D. Tanner describe in a 2012 *Life Sciences Education* paper, learning is enhanced when students work to construct their own explanations, rather than passively listening to the teacher's. That is why a properly designed automated intelligent tutoring system can foster learning outcomes as well as human instructors can, as Kurt van Lehn found in a 2011 meta-analysis in *Educational Psychologist.*

A final key advantage was the rapid improvement of the course itself. We analyzed the junctures where our thousands of students succeeded or failed and found where our course needed fine-tuning. Better still, we could capture this information on an hour-by-hour basis. For our class, human teachers analyzed the data, but an artificial-intelligence system could perform this function and then make recommendations for what a pupil could try next to improve—as online shopping sites today make automated recommendations for what book or movie you might enjoy.

Online learning is a tool, just as the textbook is a tool. The way the teacher and the student use the tool is what really counts.

***Peter Norvig** is director of research for Google. He is a fellow and councillor of the Association for the Advancement of Artificial Intelligence and co-author, with Stuart Russell, of* Artificial Intelligence: A Modern Approach *(Pearson, 2010).*

Portraits by David Despau

concerns that the experiment will falter or that her credentials will not be widely accepted, but she is confident that she will learn more with Kepler than in a traditional Rwandan university. "Most of the students here are very poor," she says. "You don't have a choice when you get a chance like this."

WHERE MOOCS MATTER MOST

BRINGING THE WORLD'S BEST college courses to some of the world's most disadvantaged people is certainly the hope—and some would say the hype—of the MOOC movement. Leaders of big MOOC platforms such as Udacity and Coursera, for-profit companies co-founded by Stanford University professors, and edX, the nonprofit platform jointly run by the Massachusetts Institute of Technology and Harvard University, are explicit in their ambition to knock down the class and geographical barriers to an advanced education. Coursera co-founder Daphne Koller laid out her world-changing goals in a TED lecture in June 2012 that was viewed more than a million times. MOOCs would "establish education as a fundamental human right, where anyone around the world with the ability and the motivation could get the skills that they need to make a better life for themselves, their families and their communities," she told an enthusiastic audience. "Maybe the next Albert Einstein or the next Steve Jobs is living somewhere in a remote village in Africa, and if we could offer that person an education, they would be able to come up with the next big idea and make the world a better place for all of us."

Nobody can argue with a goal like that. Yet educators who work in distance and online learning do argue that the MOOCs evangelists tend to oversell themselves and their product. They point out that online learning began well before MOOCs arrived and that MOOCs often do not incorporate the best, most up-to-date teaching methods. They also note that most of the developing world is not connected to the Internet and that MOOCs require skills and motivation possessed by only the very top students. "You have to find a solution that actually fits the reality of the Third World," says Tony Bates, a Canadian consultant who specializes in online learning. "Yes, content will be free in the future, but what students really need is the kind of services instructors provide. How to study, where to find information, critical analysis, learning to have original ideas in what you do, discussion and high-level thinking: all have to be supported and developed by interaction with teachers."

PROSPECTS: **Emmanuel Ngoga, Soubirous Umutoni and Pascal Uwihoreye (*top to bottom*) all participated in Kepler's prepilot course.**

That is where an experiment like Kepler comes in: blending free content from the best professors in the world with low-cost instructors who can provide personalized help and prodding. The model particularly suits a country like Rwanda, where only a tiny fraction of the population has a college degree and the number of young graduates from secondary schools is soaring. "You could build 50 universities and not meet the rising demand for college here," Hodari says. "There are people who don't go to college here, who, in an American context, would be going to Princeton."

In the U.S., the fevered discussions about the potential of MOOCs mainly center on containing or reducing the soaring cost of a college degree. Koller noted in her TED lecture, for instance, that tuition at American colleges has risen at almost twice the rate of health care costs since 1985 and proposed MOOCs as a solution. Yet in the developing world, the much larger issue is quality. The facilities and level of instruction in many countries are pitiful, and college degrees often have negligible value to globally competitive employers. Rwandans who have taken computer-programming courses, for instance, often have little experience using computers. "It's like you have a degree in swimming but learned it in a book and never jumped in a pool," says Michel Bézy, who is associate director at a small brick-and-mortar graduate program for Carnegie Mellon University in Kigali.

This is true not just in a tiny country like Rwanda but also in a giant, emerging power like India. The very best Indian universities produce excellent graduates, but the quality drops off precipitously from there. Much has been made, for instance, of the huge number of engineering graduates India produces. But of the 600,000 to 800,000 engineers who graduate in any given year, only "about 10 percent are getting a quality education," says Ashok Jhunjhunwala, a professor of electrical engineering who is regarded as one of the country's high-level academics.

Testing has helped reveal specific shortcomings. "Only about 7 percent of computer-engineering graduates meet the industry standard for basic coding," says Varun Aggarwal, co-founder and chief operating officer of Aspiring Minds, a company that conducts independent assessments of graduates on behalf of industries. A standardized "employability test" of 55,000 Indian engineering graduates in 2011 found that an alarming 42 percent could not multiply and divide numbers with decimals. More than a quarter did not have enough English to understand an engineering school curriculum. "It's a bit sad, but that's how it is," Aggarwal says. "We're graduating a huge quantity, but the quality doesn't meet the mark."

Part of the problem is poor instructors. "They are not well paid, and it's not seen as a very fashionable career to be in," Aggarwal says. "Engineers who cannot get a job in industry go on to become teachers." Another issue is the preparation of the students before they begin their higher education: many do not have proper English skills when they enter college or university, where English is the language of instruction.

If nothing changes, the situation is likely to worsen. As it is, India has one of the largest higher-education systems on the planet, with more than 600 universities and more than 33,000 colleges providing instruction to more than 20 million students. Yet the percentage

No More Lockstep Learning

Technology can humanize the classroom

By Salman Khan

Whenever people imagine virtual anything, they immediately pit it against its physical counterpart—Amazon versus physical book stores, Wikipedia versus physical encyclopedias. They assume that the virtual will replace the physical with something cheaper, faster and more efficient. In education, however, the virtual will create a very different type of disruption. We should not aim to replace the physical classroom. Instead we have an opportunity to blend the virtual with the physical and reimagine education entirely.

Today students in most classrooms sit, listen and take notes while a professor lectures. Despite there being anywhere from 20 to 300 human beings in the room, there is little to no human interaction. Exams often offer the first opportunity for the professor to get real information on how well the students digested the knowledge. If the test identifies gaps in students' understanding of a basic concept, the class still moves on to a more advanced concept.

Virtual tools are providing an opportunity to rethink this methodology. If a lecture is available online, class time can be freed for discussion, peer tutoring or professor-led exploration. If a lecture is removed from class time and we have on-demand adaptive exercises and diagnostics, there is no need to continue the factory model inherited from 19th-century Prussia—where students are pushed together at a set tempo. Instead students can progress at their own pace and continue to prove their knowledge long after the formal course is over.

Over the next 10 to 20 years blended learning will also allow us to decouple credentials from learning—today both these functions are done by the same institutions. This approach will allow anyone to prove that they have mastered a set of skills at a high level, whether they learned them on the job, at a physical school, through an online resource or, most likely, all of the above.

Perhaps the most powerful effect of this reality is what it does to the quality of lectures and other learning material in general. Traditional lecturers and textbook publishers have little to no information on how their content is being used or whether it is even effective. By coupling rich physical experiences with online tools, content creators and professors can finally have granular, up-to-date data on the efficacy of the experiences they create.

In this "blended learning" reality, the professors' role is moved up the value chain. Rather than spending the bulk of their time lecturing, writing exams and grading them, they can now interact with their students. Rather than enforcing a sit-and-listen passivity, teachers will mentor and challenge their students to take control of their own learning—the most important skill of all. Yes, for a motivated student in an impoverished part of the world, these virtual tools—assuming we can overcome accessibility issues—may facilitate most of their learning. In the developed world, the best experience will be to leverage the online tools so that the physical time can be less passive and more, well, human.

__Salman Khan__ is founder of Khan Academy, a not-for-profit educational organization for online learning based in Mountain View, Calif.

Read an interview with Khan at ScientificAmerican.com/aug2013/khan

of college-age Indians who pursue studies after secondary school is low compared with that of other countries. India's gross enrollment ratio is 17.9 percent, in contrast to China's 26.8 percent and the U.S.'s 94.8 percent. "To meet 50 percent gross enrollment, more than 30 million or 40 million new students will have to come into the higher-education system," says Anand Sudarshan, former CEO of Manipal Global Education, which runs six universities and more than 40 other educational institutions. "That's not going to happen the way things are now. Technology-driven education is absolutely the only way India can hope to responsibly catch up, both in quality and in quantity."

A GODSEND

SO ARE MOOCS THE ANSWER, in India and elsewhere?

For a small minority of exceptional students, MOOCs are a godsend. "We have a lot of people taking our courses as individual learners, and we get a lot of e-mails and other communications saying that the experience is changing their lives," says Coursera's Koller. "There are many people in the developing world who would not otherwise have access to a top education. That can't be dismissed."

Consider the case of Amol Bhave, a 17-year-old from Jabalpur, India, who was only 16 when he took a MOOC from M.I.T. called Circuits and Electronics. Bhave had been nosing around his father's engineering books since he was a child and taught himself BASIC. He got a Microsoft Certification in programming when he was still in secondary school. As a hobby, he also enjoyed electronics. He successfully completed Circuits and Electronics as a high school senior, and when edX failed to offer the follow-up course, Signals and Systems, Bhave was crestfallen. So he teamed up with two other students he met in online forums to create his own MOOC version of the course—based on M.I.T.'s videotaped lectures and online quizzes, along with other interactive elements created by Bhave. "It was my own code and everything from scratch," Bhave says. Roughly 1,100 students took part in the course. Bhave cited this effort when he applied to M.I.T. as a full-time student this year. "On March 14 the admissions decisions were out. And guess what? I got in!" Bhave says. "My family and I were so excited. This was the first time anyone from my city was going to M.I.T. for undergraduate studies."

The anecdote can be read two ways. One, an M.I.T. MOOC opened a fantastic window of opportunity for a young man living in central India, and two, MOOCs cannot fully replace traditional courses, as Bhave's highest aspiration was to fly to the U.S. and attend M.I.T. in person. The reasons Bhave craves the M.I.T. classroom experience are clear: for starters, it is difficult to study hard sciences, as Bhave would like to do, without being able to do hands-on research in a lab. More important, Bhave cannot get an M.I.T. degree

An Opportunity for India

Online courses may help alleviate faculty shortages and improve education

By Pawan Agarwal

Digital technologies have the potential to dramatically transform Indian higher education. A new model built around massive open online courses (MOOCs) that are developed locally and combined with those provided by top universities abroad could deliver higher education on a scale and at a quality not possible before.

University enrollment in India is huge and growing. It surpassed the U.S.'s enrollment in 2010 and became second only to China that year. Every day in India 5,000 students enroll at a university and 10 new institutions open their doors.

At more than 3 percent of the country's GDP, India's spending on higher education is one of the highest in the world. Yet per-student spending is among the lowest. While recent expansion has widened access to universities, it has further reduced per-student spending and aggravated already acute faculty shortages. As a result, quality has declined.

India must continue to expand access to higher education while preserving quality and reducing costs. This situation is not unique to India, but given its enormous size and unique position, India's challenges are formidable. Digital technologies, particularly the extensive use of MOOCs, could help.

India has experimented with online classes before, but their impact has been marginal. A decade ago the country began using the Internet to distribute video and Web-based courses under a government-funded program, the National Program on Technology Enhanced Learning. Developers created more than 900 courses, focused mainly on science and engineering, with about 40 hours of instruction each. With limited interactivity and uneven quality, these courses failed to attract a large body of students.

MOOCs have given Indian academics a better sense of how a lecture could be from online studies, and a degree is key to pursuing a career.

The vast majority of Indians, in any case, may not have the drive or the smarts to do what Bhave did. He also had the benefit of coming from a family that was able to provide him with a computer and reliable Internet access. His father is an engineer and could afford to send Bhave to a private secondary school. Internet penetration is getting better in India, but it is still dismal: about 10 percent of Indians used the Internet in 2011. Reliable electricity remains a problem in much of the country, where the per capita annual income is less than $1,500. For hundreds of millions of Indians, a computer is an unimaginable luxury.

Yet technology is spreading and getting cheaper. Even a landlocked country like Rwanda is crisscrossed with fiber-optic cables and getting more wired by the year. Computing devices are becoming more affordable: at the behest of India, U.K.-based firm Datawind has produced a basic Android tablet for $40.11, and the Indian government has provided it to students for about half that price. The Aakash 2 cannot compete with top-of-the-line tablets. But for the price, it could be revolutionary. Datawind aims to ship a million of the tablets to India this year. "When I held that thing in my hand, I thought that this is going to change the world, and the world doesn't know it yet," says Andrew Ng, who co-founded Coursera with Koller.

MOOCs are evolving, too. Michael Horn, co-founder of the Clayton Christensen Institute for Disruptive Innovation, a think tank that focuses on education and health care innovation, likens today's MOOCs to the earliest moving pictures. "The first movies were films of stage plays, and they look silly and absurd," he says. "MOOCs today are essentially filming the stage plays. They are filming the lectures and splicing them up." It is partly for this reason that less than 10 percent of people who sign up for MOOCs actually complete them. Horn expects online lectures to steadily become more engaging. The aim is to produce interactive courses that will not only teach students but also learn from them, so the courses will adapt and tailor themselves to individual skills and needs.

Some educators even envisage a broad decoupling of learning and assessment: a student who takes MOOCs and then gets tested and earns a competency-based degree at a high level could become more competitive in the job market than a graduate with a traditional degree from a brick-and-mortar university.

66%

Share of U.S. college presidents who say they find adaptive-learning and testing technologies promising

DATA SOURCE: "THE 2013 INSIDE HIGHER ED SURVEY OF COLLEGE AND UNIVERSITY PRESIDENTS," BY INSIDE HIGHER ED AND GALLUP. INSIDE HIGHER ED, 2013

That is still in a hypothetical future, however. For now, students do not often see a tangible benefit to taking MOOCs: in the developing world, probably more so than elsewhere, youngsters need to have confidence that a particular education will lead to a job and a paycheck. "Students need to see a clear continuum between taking a course, getting a certificate for the course and having employers recognize that certificate," Aggarwal says. "The courses need to conform to what the industry is looking for. If that virtuous cycle is built and is clear to the student, then MOOCs can scale."

MOOC providers are aiming to award credentials that will be acceptable to colleges and employers, but that is still in the early stages. Part of the challenge is to develop safeguards against cheating that are seen as reliable. One method requires students to go to testing centers; other methods are technological. "We have something called Signature Track, where we ask someone to show a photo ID from the start, and when you do homework, you're asked to take a photo and provide a typing sample," Ng says. "Your typing rhythm is hardened to your being. It is very difficult for you to type like I type or for me to type as you do." The process is called keystroke biometrics, and it can be used to ensure that someone completing an assignment is the same person who signed up for the course.

Coursera is also working with an outfit called ProctorU, which monitors exams by Web cam. ProctorU asks test takers to show one or more forms of ID and to use their computer to scan the room to be sure no test aids are posted. Students may also have to fill out a multiple-choice quiz about their personal background—based on information gathered from public databases—to verify their identity. A ProctorU employee then watches students by webcam during the test. The process is more difficult to conduct overseas, but it is doable.

MOOC providers also see credentialing as a way to monetize their services. Coursera courses are free on an individual basis, for instance, but credentials are not. At the moment, if a student opts to take a Signa-

restructured into short, self-contained segments with high interactivity to engage students more effectively. Plans are afoot for the Indian Institutes of Technology, widely considered to be among the world's top engineering schools, to offer three basic IT courses in data structure, programming and algorithms to hundreds of thousands of undergraduates through MOOCs. These courses would award credits and count toward degrees.

It helps that India is full of young people who possess a high comfort level with technology. Indians are among the most aggressive users of MOOCs. Of the 2.9 million registered users of Coursera in March, more than 250,000 were from India, second only to those from the U.S.

Yet we still need to find the right model to use MOOCs in an Indian context. With a decade of experience in this space and a vibrant technology ecosystem, India will most likely find its way soon.

Pawan Agarwal *is adviser for higher education for the Indian government's Planning Commission. These are his personal views.*

"Experimentation Is Key"

The future of on-campus learning lies in the right combination of digital and traditional tools

By Robert A. Lue

When I taught my first online course more than a decade ago, I was an oddity in my department. My primary motivation was to share information about the biology of HIV as part of an overall effort to combat the many misconceptions surrounding AIDS in the public mind. The course was made up of video captures of in-class lectures that were transmitted to the world as part of our continuing education programs.

Today the situation is markedly different. In May 2012 Harvard University and the Massachusetts Institute of Technology announced the creation of edX, an institutional partnership aimed at expanding access to high-quality education through online classes while also transforming teaching and learning on our respective campuses. Faculty interest in online teaching has climbed, even as healthy dialogue continues on the potential impact of making these classes so widely available on the Web.

Online classes are not just about sharing educational materials via the Internet; they are also about developing new ways of teaching based on those materials for both on-campus and online audiences. Many of my colleagues are already applying digital tools from online courses in an effort to transform student experiences here in Cambridge, Mass. For example, every video tutorial and interactive assessment developed for David J. Malan's introductory course to computer science fully supports Harvard undergraduates in his on-campus course. The software, which he designed to give students instantaneous feedback on the quality of their code, is as useful for students on campus as it is for those online. Likewise E. Francis Cook and Marcello Pagano of the Harvard School of Public Health

ture Track class from Duke University on Coursera, he or she will pay a fee of less than $100. After completing the course and passing exams, the student gets a "verified certificate" of completion with a Duke logo on it. For a handful of Coursera classes currently accredited by the American Council on Education, credit recommendations from that organization—which are accepted at many traditional institutions—are available. The cost is $100 to $190. Coursera also offers financial aid to participants who cannot afford those fees.

Yet such high-tech solutions on a broad scale still seem far-fetched for parts of the world where clean water and proper sanitation are in short supply. For now, the primary focus in India is to explore the use of MOOC technology to enhance the quality of teaching within existing institutions. Microsoft Research is working on a pilot project to develop online classes in the style of MOOCs, taught by leading Indian professors, which would fit the existing curriculum at Indian engineering schools. The program is called Massively Empowered Classrooms, or MEC. "There is no single answer for everybody," says Jhunjhunwala, who believes that most Indian students, because of language and culture issues, would have trouble comprehending online courses offered by American universities. He recalls being utterly perplexed while taking a chemistry course in college because he could not understand the accent of his American professor. "Just taking something from outside and importing it doesn't work," he says. "It has never worked."

Students do not often see a tangible benefit to taking MOOCs: in the developing world, youngsters need to have confidence that a particular education will lead to a job and a paycheck.

MOOC proponents counter that top-notch textbooks are used all over the world and that online classes can be seen as a kind of digital textbook. Courses can be designed for a wide variety of audiences. Europeans are developing their own MOOC platforms, and the big American MOOC providers are signing up foreign universities to provide courses in languages other than English. "Online education is still in its infancy now," says Bhave, who brims with teenage idealism. "But it certainly has the potential to change the face of the developing world." Based on his own experience, he observes, "there is an education revolution waiting to happen in the coming years."

A HIGH-STAKES EXPERIMENT

THE EDUCATORS at Kepler are not waiting. To them, the only workable model is clear: delivering the best instruction from the best teachers online but with significant hands-on support and classroom interaction. "The idea of just dropping MOOCs on Africans or others without facilitation and without assistance is a nonstartdeveloped a novel online course in biostatistics and epidemiology that they will use this fall to support a flipped classroom model—in which students watch lectures or other course material online and come to class for active discussions with instructors and peers.

The rapid evolution of digital resources such as video, interactive multimedia and new modes of assessment challenges us to reimagine what we can and should do when we are face-to-face with our students. As I develop an online course on cellular metabolism, for instance, I hypothesize that the combination of animation with embedded and self-paced assessments will communicate the intricacies of electron transfer more effectively than that portion of my traditional lecture. After rebalancing class assignments to include both reading and online materials while maintaining the same overall workload, I nonetheless gain time with my students in the classroom to discuss and critically analyze the metabolic consequences of experimentally disrupting electron transfer. In other words, I can spend more time on the concepts that are most challenging for my students. In this regard, the flipped classroom may provide students with greater and more effective faculty attention than ever before.

Underlying all these exciting efforts is the awareness that experimentation is key and that we do not yet know how to best harness the enormous positive potential of the online revolution for on-campus learning. This is why every course or module in HarvardX—Harvard's university-wide digital-education initiative that includes participation in edX—has an associated research component. We measure student progress as it relates to the sequence of course material, how that material was delivered (that is, lecture versus video animation), whether the instructor used interactive assessments, and other parameters. Such complementary research with each online course will form the basis for improvements in pedagogy both online and on campus. Indeed, institutions of higher education must engage with this process of exploration if we are to develop effective new models that broaden access to high-quality educational content while sustaining and indeed growing the in-person structures that support the joint enterprise of research, scholarship and teaching.

__Robert A. Lue__ is Richard L. Menschel Faculty Director of the Derek Bok Center for Teaching and Learning, faculty director of HarvardX, and professor in the department of molecular and cellular biology at Harvard University.

er," Hodari says. "A lot of students haven't been taught how to use a computer. Really simple stuff is complicated: launching a program, closing a program, even typing."

The first teaching fellow to join Kepler was Christine Yarng, a former teacher at a Knowledge Is Power Program (KIPP) charter school in Austin, Tex. Emma Stellman, the co-founder of a premier charter school in Cambridge, Mass., is designing the curriculum. Both are working for nonprofit wages in a remote corner of the globe because they believe that quality education can dramatically transform lives and because they have a hunger for challenge and adventure. Stellman aims to use chunks of various MOOCs and combine them in ways that are most suitable to her Rwandan students. The emphasis, at first, will be on learning how to learn—particularly in a digital context—and on quantitative analysis and critical thinking. "Employers are dying because they can't find people who can think for themselves," Stellman says. "And the students become very proud when they realize they can have their own ideas. You see these lightbulbs go on: it's a beautiful phenomenon and very empowering."

The Kepler prepilot class was conducted to identify problems and come up with solutions before the full program in the fall. By the fifth week Yarng and Stellman had learned several important lessons. They needed better Internet access, for starters, and so plan to move into new offices connected to Rwanda's fiber-optic network this summer. More important, they realized that many students needed significant English-language training to be able to follow online lectures and analyze complex subject matter. (In recent years Rwanda has switched from French to English as the primary language of instruction in schools.) Kepler now plans to conduct intensive English classes during an orientation period before the fall session begins and to assign a lot of writing in English during the regular term. "And when we're done writing," Stellman says, "we'll write some more."

Ideally, Hodari would like to expand Kepler in Rwanda and then export the model to other countries. That depends, however, on how the next two years go. "This is a pilot," he says. "Our focus is on experimentation. There's been a lot of heavy breathing about changing the world but not a lot of experience in doing it. We want to spend two years testing the model—to see which pedagogical methods get the best student results." Above all, Hodari wants to be sure the Kepler experiment succeeds, if only because 50 very hopeful Rwandans have no plan B.

__Jeffrey Bartholet__ is a veteran foreign correspondent and former Washington bureau chief at Newsweek.

$425 million

Approximate amount of money venture capitalists invested in technology start-ups aimed at K–12 schools in 2012

DATA SOURCE: "THE NMC HORIZON REPORT: 2013 K–12 EDITION," BY L. JOHNSON, S. ADAMS BECKER, M. CUMMINS, V. ESTRADA, A. FREEMAN AND H. LUDGATE. THE NEW MEDIA CONSORTIUM, 2013

ADAPTIVE TECHNOLOGY

MACHINE LEARNING

Schools and universities are embracing technology that tailors content to students' abilities and takes teachers out of the lecturing business. But is it an improvement?

By Seth Fletcher

When Arnecia Hawkins enrolled at Arizona State University last fall, she did not realize she was volunteering as a test subject in an experimental reinvention of American higher education. Yet here she was, near the end of her spring semester, learning math from a machine. In a well-appointed computer lab in Tempe, on Arizona State's desert resort of a campus, she and a sophomore named Jessica were practicing calculating annuities. Through a software dashboard, they could click and scroll among videos, text, quizzes and practice problems at their own pace. As they worked, their answers, along with reams of data on the ways in which they arrived at those answers, were beamed to distant servers. Predictive algorithms developed by a team of data scientists compared their stats with data gathered from tens of thousands of other students, looking for clues as to what Hawkins was learning, what she was struggling with, what she should learn next and how, exactly, she should learn it.

Having a computer for an instructor was a change for Hawkins. "I'm not gonna lie—at first I was really annoyed with it," she says. The arrangement was a switch for her professor, too. David Heckman, a mathematician, was accustomed to lecturing to the class, but he had to take on the role of a roving mentor, responding to raised hands and coaching students when they got stumped. Soon, though, both began to see some benefits. Hawkins

MITCH PAYNE (*photograph*)

Illustration by Kyle Bean


A B C D

liked the self-pacing, which allowed her to work ahead on her own time, either from her laptop or from the computer lab. For Heckman, the program allowed him to more easily track his students' performance. He could open a dashboard that told him, in granular detail, how each student was doing—not only who was on track and who was not but who was working on any given concept. Heckman says he likes lecturing better, but he seems to be adjusting. One definite perk for instuctors: the software does most of the grading for them.

At the end of the term, Hawkins will have completed the last college math class she will probably ever have to take. She will think back on this data-driven course model—so new and controversial right now—as the "normal" college experience. "Do we even have regular math classes here?" she asks.

BIG DATA TAKES EDUCATION

ARIZONA STATE'S DECISION to move to computerized learning was born, at least in part, of necessity. With more than 70,000 students, Arizona State is the largest public university in the U.S. Like institutions at every level of American education, it is going through some wrenching changes. The university has lost 50 percent of its state funding over the past five years. Meanwhile enrollment is rising, with alarmingly high numbers of students showing up on campus unprepared to do college-level work. "There is a sea of people we're trying to educate that we've never tried to educate before," says Al Boggess, director of the Arizona State math department. "The politicians are saying, 'Educate them. Remediation? Figure it out. And we want them to graduate in four years. And your funding is going down, too.' "

Two years ago Arizona State administrators went looking for a more efficient way to shepherd students through basic general-education requirements—particularly those courses, such as college math, that disproportionately cause students to drop out. A few months after hearing a pitch by Jose Ferreira, the founder and CEO of the New York City adaptive-learning start-up Knewton, Arizona State made a big move. That fall, with little debate or warning, it placed 4,700 students into computerized math courses. Last year some 50 instructors coached 7,600 Arizona State students through three entry-level math courses running on Knewton software. By the fall of 2014 ASU aims to adapt six more courses, adding another 19,000 students a year to the adaptive-learning ranks. (In May, Knewton announced a partnership with Macmillan Education, a sister company to *Scientific American*.)

Adapt or Die

A sampling of the 70-odd companies rushing to rule the adaptive-learning market.

CogBooks

A Scottish company that specializes in adaptive corporate-training software (subjects include international trade and sales and communication), CogBooks has announced plans to enter the U.S. higher-education market.

DreamBox Learning

Based in Bellevue, Wash., DreamBox creates adaptive online math courses, many of which are aligned with the Common Core standards, for use in elementary school classrooms.

Knewton

The five-year-old New York City–based company, whose software underpins Arizona State University's adaptive math courses, builds a data-crunching "platform" on which educators add their own lesson plans, quizzes, videos and other materials.

Area9

This Danish firm's adaptive platform underpins McGraw-Hill's LearnSmart software, which provides personalized instruction to high school and college students, as well as professionals.

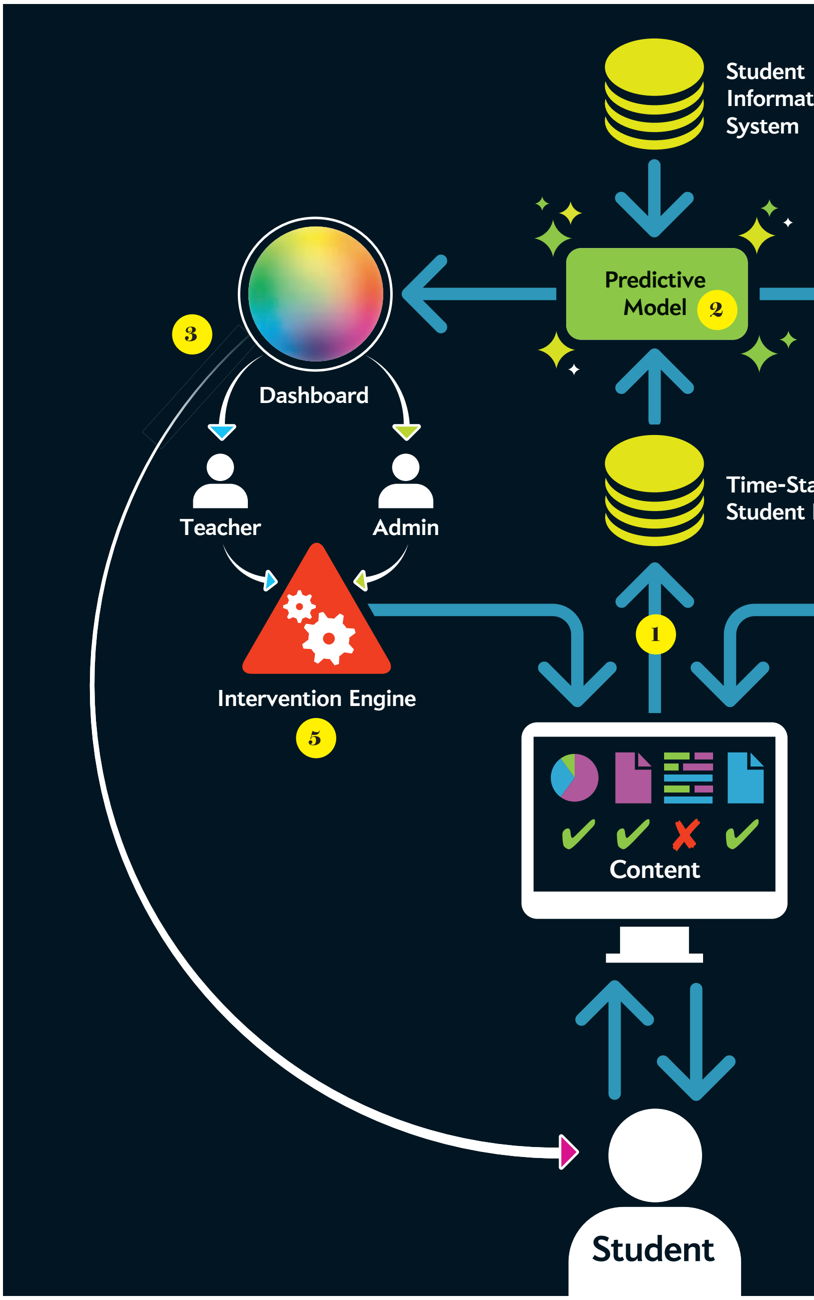
PrepU

PrepU (which is part of Macmillan New Ventures, a sister company of *Scientific American*) has developed an adaptive "quizzing engine" for high school students preparing for Advanced Placement exams, college students learning biology, and nursing students, among others.

Arizona State is one of the earliest, most aggressive adopters of data-driven, personalized learning. Yet educational institutions at all levels are pursuing similar options as a way to cope with rising enrollments, falling budgets and more stringent requirements for student achievement. Public primary and secondary schools in 45 states and the District of Columbia are rushing to implement new, higher standards in English-language arts and mathematics known as the Common Core state standards, and those schools need new instructional materials and tests to make that happen. Around half of those tests will be online and adaptive, meaning that a computer will tailor questions to each student's ability and calculate each student's score [see "Why We Need High-Speed Schools," on page 69]. School systems are experimenting with a range of other adaptive programs, from math and reading lessons for elementary school students to "quizzing engines" that help high school students prepare for Advanced Placement exams. The technology is also catching on overseas. The 2015 edition of the Organization for Economic Co-operation and Development's Program for International Student Assessment (PISA) test, which is given to 15-year-olds (in more than 70 nations and economies so far) every three years, will include adaptive components to evaluate hard-to-measure skills such as collaborative problem solving.

Proponents of adaptive learning say that technology has finally made it possible to deliver individualized instruction to every student at an affordable cost—to discard the factory model that has dominated Western education for the past two centuries. Critics say it is data-driven learning, not traditional learning, that threatens to turn schools into factories. They see this increasing digitization as yet another unnecessary sellout to for-profit companies that push their products on teachers and students in the name of "reform." The supposedly advanced tasks that computers can now barely pull off—diagnosing a student's strengths and weaknesses and adjusting materials and approaches to suit individual learners—are things human teachers have been doing well for hundreds of years. Instead of delegating these tasks to computers, opponents say, we should be spending more on training, hiring and retaining good teachers.

And while adaptive-learning companies claim to have nothing but the future of America's children in mind, there is no denying the potential for profit. Dozens of them are rushing to get in on the burgeoning market for instructional technology, which is now a multibillion-dollar industry [*see box at left*]. As much as 20 percent of instructional content in K–12 schools is already delivered digitally, says



Teacher's Assistant

In a typical adaptive-learning system, students read text and complete exercises on a computer that feeds their progress into a database 1. Analytical software then combines these time-stamped data with information on the student's background, stored at the school or district level, to predict how well he or she will perform in the class 2. Teachers and administrators can view the student's progress on a dashboard 3, and the same predictive model also pipes information back into the adaptive-learning system 4, which adjusts its teaching strategy to the student. If necessary, educators and administrators can override the adaptive program and intervene 5 to change the content the student is seeing.

SOURCE: "ENHANCING TEACHING AND LEARNING THROUGH EDUCATIONAL DATA MINING AND LEARNING ANALYTICS: AN ISSUE BRIEF," BY U.S. DEPARTMENT OF EDUCATION, OFFICE OF EDUCATIONAL TECHNOLOGY, OCTOBER 2012

Adam Newman, a founding partner of the market-analysis firm Education Growth Advisors. Although adaptive-learning software makes up only a small slice of the digital-instruction pie—around $50 million for the K–12 market—it could grow quickly. Newman says the concept of adaptivity is already very much in the water in K–12 schools. "In K–12, the focus has been on differentiating instruction for years," he says. "Differentiating instruction, even without technology, is really a form of adaptation."

Higher-education administrators are warming up to adaptivity, too. In a recent Inside Higher Ed/Gallup poll, 66 percent of college presidents said they found adaptive-learning and testing technologies promising. The Bill & Melinda Gates Foundation has launched the Adaptive Learning Market Acceleration Program, which will issue 10 $100,000 grants to U.S. colleges and universities to develop adaptive courses that enroll at least 500 students over three semesters. "In the long term—20 years out—I would expect virtually every course to have an adaptive component of some kind," says Peter Stokes, an expert on digital education at Northeastern University. That will be a good thing, he says—an opportunity to apply empirical study and cognitive science to education in a way that has never been done. In higher education in particular, "very, very, very few instructors have a formal education in how to teach," he says. "We do things, and we think they work. But when you start doing scientific measurement, you realize that some of our ways of doing things have no empirical basis."

Graphic by Arno Ghelfi

Promise and Peril

Technology can inspire creativity or dehumanize learning

By Diane Ravitch

Technology is transforming American education, for good and for ill. The good comes from the ingenious ways that teachers encourage their students to engage in science projects, learn about history by seeing the events for themselves and explore their own ideas on the Internet. There are literally thousands of Internet-savvy teachers who regularly exchange ideas about enlivening classrooms to heighten student engagement in learning.

The ill comes in many insidious forms.

One of the malign manifestations of the new technology is for-profit online charter schools, sometimes called virtual academies. These K–12 schools recruit heavily and spend many millions of taxpayer dollars on advertising. They typically collect state tuition for each student, which is removed from the local public schools' budget. They claim to offer customized, personalized education, but that's just rhetoric. They have high dropout rates, low test scores and low graduation rates. Some have annual attrition rates of 50 percent. But so long as the virtual schools keep luring new students, they are very profitable for their owners and investors.

Another dubious use of technology is to grade essays. Major testing companies such as Pearson and McGraw-Hill are using software to score written test answers. Machines can grade faster than teachers, but they cannot evaluate factual statements or the imaginative use of language. A student may write that the World War II began in 1839, and the machine won't object. Students will learn to write according to the formula that the machine likes, at the expense of accuracy, creativity and imagination. Worse, the teacher will abandon the important job of reading what his or her students write and will be less

THE SCIENCE OF ADAPTIVITY

IN GENERAL, "adaptive" refers to a computerized-learning interface that constantly assesses a student's thinking habits and automatically customizes material for him or her. Not surprisingly, though, competitors argue ferociously about who can claim the title of true adaptivity. Some say that a test that does nothing more than choose your next question based on whether you get the item in front of you correct—a test that steers itself according to the logic of binary branching—does not, in 2013, count as fully adaptive. In this view, adaptivity requires the creation of a psychometric profile of each user, plus the continuous adjustment of the experience based on that person's progress.

To make this happen, adaptive-software makers must first map the connections among every concept in a piece of learning material. Once that is done, every time a student watches a video, reads an explanation, solves a practice problem or takes a quiz, data on the student's performance, the effectiveness of the content, and more flow to a server. Then the algorithms take over, comparing that student with thousands or even millions of others. Patterns should emerge. It could turn out that a particular student is struggling with the same concept as students who share a specific psychometric profile. The software will know what works well for that type of student and will adjust the material accordingly. With billions of data points from millions of students and given enough processing power and experience, these algorithms should be able to do all kinds of prognostication, down to telling you that you will learn exponents best between 9:42 and 10:03 A.M.

They should also be able to predict the best way to get you to remember the material you are learning. Ulrik Juul Christensen, CEO of Area9, the developer of the data-analysis software underpinning McGraw-Hill's adaptive LearnSmart products, emphasizes his company's use of the concept of memory decay. More than two million students currently use LearnSmart's adaptive software to study dozens of topics, either on their own or as part of a course. Research has shown that those students (all of us, really) remember a new word or fact best when they learn it and then relearn it when they are just on the cusp of forgetting it. Area9's instructional software uses algorithms to predict each user's unique memory-decay curve so that it can remind a student of something learned last week at the moment it is about to slip out of his or her brain forever.

Few human instructors can claim that sort of prescience. Nevertheless, Christensen dismisses the idea that computers could ever replace teachers. "I don't think we are so stupid that we would let computers take over teaching our kids," he says.

BACKLASH

IN MARCH, Gerald J. Conti, a social studies teacher at Westhill High School in Syracuse, N.Y., posted a scathing retirement letter to his Facebook page that quickly became a viral sensation. "In their pursuit of Federal tax dollars," he wrote, "our legislators have failed us by selling children out to private industries such as Pearson Education," the educational-publishing giant, which has partnered with Knewton to develop products. "My profession is being demeaned by a pervasive atmosphere of distrust, dictating that teachers cannot be permitted to develop and administer their own quizzes and tests (now titled as generic 'assessments') or grade their own students' examinations." Conti sees big data leading not to personalized learning

Take an adaptive quiz on state capitals at ScientificAmerican.com/aug2013/learn-smart informed about how they think. That is a loss for the quality of education. Frankly, it is a problem with online assessment in general, as the job of testing is shifted from the teacher to a distant corporation; the last round of state testing saw computer breakdowns in several states. In addition, it is only a matter of time until students hack into the tests.

The most worrisome use of technology is to accumulate and store personal, confidential data about every public school student. The Bill & Melinda Gates Foundation put up close to $100 million to create the Shared Learning Collaborative, now called inBloom, with partners Wireless Generation (owned by Rupert Murdoch's News Corporation) and Carnegie Corporation. It will gather student data from several districts and states, including New York, Georgia, Delaware, Kentucky and Louisiana (some of these states are reconsidering because of objections from parents). The data will be stored on a cloud managed by Amazon. On the cloud will be students' names, addresses, grades, test scores, disability status, attendance, program participation and many other details about students that teachers and schools are not allowed to release.

Who needs all this personal information, and why is it being shared? Advocates say that the goal is to create better products for individual students. Critics believe that the information will be given or sold to vendors, who will use it to market products to children and their parents. No one knows whether the data will be secure; snoops frequently hack into databases and clouds.

Until recently, the release of personal student data without parental consent would have been prohibited by a 1974 federal law known as FERPA (the Family Educational Rights and Privacy Act). In 2011, however, the U.S. Department of Education revised the FERPA regulations, making this data project legal. The electronic Privacy Information Center (EPIC) has sued the Department of Education in federal court for watering down FERPA and allowing students' data to be released to third parties without parental consent.

Here is the conundrum: teachers see technology as a tool to inspire student learning; entrepreneurs see it as a way to standardize teaching, to replace teachers, to make money and to market new products. Which vision will prevail?

Diane Ravitch *is a historian of American education and a research professor of education at New York University. Her most recent book—*The Death and Life of the Great American School System: How Testing and Choice Are Undermining Education*—was a national best seller in 2010.*

for all but to an educational monoculture: "STEM [science, technology, engineering and mathematics] rules the day, and 'data driven' education seeks only conformity, standardization, testing and a zombie-like adherence to the shallow and generic Common Core."

Conti's letter is only one example of the backlash building against tech-oriented, testing-focused education reform. In January teachers at Garfield High School in Seattle voted to boycott the Measures of Academic Progress (MAP) test, administered in school districts across the country to assess student performance. After tangling with their district's superintendent and school board, the teachers continued the boycott, which soon spread to other Seattle schools. Educators in Chicago and elsewhere held protests to show solidarity. In mid-May it was announced that Seattle high schools would be allowed to opt out of MAP, as long as they replaced it with some other evaluation.

It would be easy for proponents of data-driven learning to counter these protests if they could definitely prove that their methods work better than the status quo. But they cannot do that, at least not yet. Empirical evidence about effectiveness is, as Darrell M. West, an adaptive-learning proponent and founder of the Brookings Institution's Center for Technology Innovation, has written, "preliminary and impressionistic." Any accurate evaluation of adaptive-learning technology would have to isolate and account for all variables: increases or decreases in a class's size; whether the classroom was "flipped" (meaning homework was done in class and lectures were delivered via video on the students' own time); whether the material was delivered via video, text or game; and so on. Arizona State says 78 percent of students taking the Knewton-ized developmental math course passed, up from 56 percent before. Yet it is always possible that more students are passing not because of technology but because of a change in policy: the university now lets students retake developmental math or stretch it over two semesters without paying tuition twice.

Even if proponents of adaptive technology prove that it works wonderfully, they will still have to contend with privacy concerns. It turns out that plenty of people find pervasive psychometric-data gathering unnerving. Witness the fury that greeted inBloom earlier this year. InBloom essentially offers off-site digital storage for student data—names, addresses, phone numbers, attendance, test scores, health records—formatted in a way that enables third-party education applications to use it. When inBloom was launched in February, the company announced partnerships with school districts in nine states, and parents were outraged. Fears of a "national database" of

80%

Approximate share of educational apps that target children. This year educational apps were the second most downloaded on iTunes, surpassing entertainment

SOURCE: "THE NMC HORIZON REPORT: 2013 K-12 EDITION," BY L. JOHNSON, S. ADAMS BECKER, M. CUMMINS, V. ESTRADA, A. FREEMAN AND H. LUDGATE. THE NEW MEDIA CONSORTIUM, 2013 student information spread. Critics said that school districts, through inBloom, were giving their children's confidential data away to companies who sought to profit by proposing a solution to a problem that does not exist. Since then, all but three of those nine states have backed out.

This might all seem like overreaction, but to be fair, adaptive-education proponents already talk about a student's data-generated profile following them throughout their educational career and even beyond. Last fall the education-reform campaign Digital Learning Now released a paper arguing for the creation of "data backpacks" for pre-K–12 students—electronic transcripts that kids would carry with them from grade to grade so that they will show up on the first day of school with "data about their learning preferences, motivations, personal accomplishments, and an expanded record of their achievement over time." Once it comes time to apply for college or look for a job, why not use the scores stored in their data backpacks as credentials? Something similar is already happening in Japan, where it is common for managers who have studied English with the adaptive-learning software iKnow to list their iKnow scores on their resumes.

THIS IS NOT A TEST

IT IS FAR from clear whether concerned parents and scorned instructors are enough to stop the march of big data on education. "The reality is that it's going to be done," says Eva Baker, director of the Center for the Study of Evaluation at the University of California, Los Angeles. "It not going to be a little part. It's going to be a big part. And it's going to be put in place partly because it's going to be less expensive than doing professional development."

That does not mean teachers are going away. Nor does it mean that schools will become increasingly test-obsessed. It could mean the opposite. Sufficiently advanced testing is indistinguishable from instruction. In a fully adaptive classroom, students will be continually assessed, with every keystroke and mouse click feeding a learner profile. High-stakes exams could eventually disappear, replaced by the calculus of perpetual monitoring.

Long before that happens, generational turnover could make these computerized methods of instruction and testing, so foreign now, unremarkable, as they are for Arizona State's Hawkins and her classmates. Teachers could come around, too. Arizona State's executive vice provost Phil Regier believes they will, at least: "I think a good majority of the instructors would say this was a good move. And by the way, in three years 80 percent of them aren't going to know anything else."

Seth Fletcher *is a senior editor at* Scientific American.

Education Is for the (Angry) Birds

What the world's most addictive video game will teach us next

By Peter Vesterbacka

Many people believe that learning should feel like work. Often when families move to Finland from other countries and put their children in day care, they worry that the schools are not teaching them enough. They say, "The kids are not learning anything. They're just playing." But that's the whole point: humans learn by playing, and that philosophy is built into the Finnish school system. My kids have a short school day and little homework, yet Finnish students earn some of the highest scores of any nation on international tests.

What can games really teach you? There is a well-known example in Finland. Researchers have noticed that Finnish boys speak better English than Finnish girls. The reason for that observation—which they documented in a number of studies—is that boys play more video games. Because the games are in English, players have built larger vocabularies. The point here is that the boys did not set out to learn English, but they learned it while having fun.

We have never seen ourselves as exclusively a games company, and now we are doing more and more with education. Last year we partnered with NASA on Angry Birds Space, which teaches kids about microgravity. We are also working with CERN to develop games and animations to teach the principles of quantum physics to children as young as four and six years old. Angry Birds already has physics: you learn about trajectories even without thinking much about it. We are taking the same kind of approach with CERN but taking it a bit further so you can get more deeply into math, physics and science in a fun way. Finally, we are branching out into languages, and we have developed an English-learning game for the Chinese market based on the Moon Festival, which has enormous cultural significance there.

I do not believe that the future of education is all digital. It is very important for kids to get to do real things, to work with objects that they can touch and feel. In a few years I believe that more than half of our business will be physical. Already we have a burgeoning publishing business: we have storybooks and activity books based on our video game characters, and we are working on a line of educational toys. What has been done so far to combine the physical and the virtual has been very limited, which is where I think the greatest opportunity lies. There will be tremendous innovation in that area in the years to come.

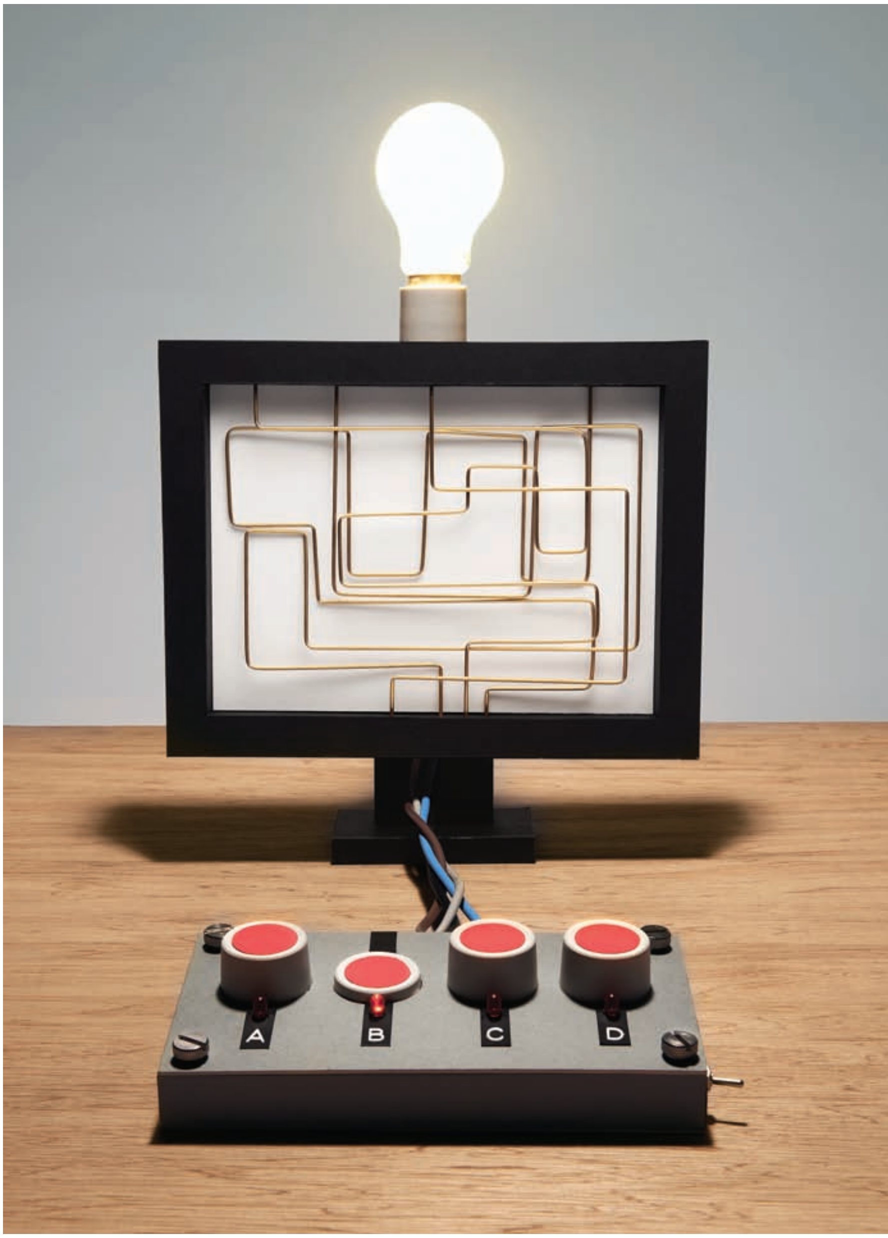
Peter Vesterbacka *is chief marketing officer of Rovio Entertainment, the Finland-based company behind Angry Birds.*

THE FUTURE OF TESTING

WHY WE NEED HIGH-SPEED SCHOOLS

Greater broadband access will bring the latest digital tools to more teachers and students

By Arne Duncan



MITCH PAYNE (*photograph*)

Recently I had the opportunity to visit the future. It was located in Kristie Ford's classroom in Detroit.

On the day I was invited, the class of fifth and sixth graders was a hive of activity and motion, which Ford did not need to closely direct. Instead as she talked individually with a few students, others worked independently in small clusters discussing their study of the solar system or sprawled on the floor constructing 3-D models. Still others were enmeshed in learning games and apps on laptops.

But as Ford and others at the Brenda Scott Academy for Theatre Arts made clear, the bustle was about more than fun and engaging tasks and cool technology. Underlying that surface appearance was a plan—backed by digital technology—to tailor learning to each student's needs.

In traditional classrooms, students complete a lesson and move on to the next when it is time for the whole class to do so—regardless of whether they have mastered it or they are already well ahead. Here each student worked at her or his own pace, taking as much or little time as necessary to complete one lesson and then moving on to the next. Each child worked from an individual learning plan, and Ford could offer students material from a wide variety of digital sources—including traditional publishers, freely available "open" educational resources and her own original material.

The digital revolution has changed nearly every aspect of daily life—from how Americans shop, to how they communicate, to how they find a date. Schools—many of which have been slow to embrace innovation—are beginning to let in this digital revo-

Illustration by Kyle Bean

lution. For the students in Ford's class, the benefits are clear. Yet what is happening at her school is not the norm, and the danger is that digital-learning tools could miss their potential to close long-standing learning gaps and instead disproportionately benefit students who already have the most advantages. That is why the Obama administration has taken steps to ensure access and equity in digital learning: with funding for innovations that tailor learning to students' needs; with funding for new assessments that are part of a state-led effort to raise learning standards; and with a major five-year challenge from the president to give virtually every student access to broadband and wireless Internet. But it will take everyone—educators, technology developers, systems leaders—working together to make sure that students everywhere enjoy the opportunities that Ford's students do.

TECHNOLOGY AND CHANGE

TODAY'S ELEMENTARY SCHOOL students will be completing college around 2030. Their careers will take them deep into the second half of the 21st century. It is a good bet that the economy they enter will rely even more on knowledge and technology than ours does today. Our schools must prepare students for that future, and we had better get it right. Their preparedness will decide our economic strength as a country.

Digital technology will play an important part in ensuring they are ready. For students and teachers alike, it will make the walls of school porous as never before. Teachers can connect with one another virtually, not just to share lesson plans but also to mentor and share strategies for effective teaching through online collaboration. Via Web-enabled communication and streaming video, students—particularly those who are geographically isolated or who are taking advanced courses with limited enrollment—can connect with experts who might be thousands of miles away and can use nearly limitless instructional resources.

Meanwhile developers are creating mobile learning apps that are useful almost everywhere. Many popular educational apps are co-designed by teachers and software developers. Technology is also making it possible to blend online and face-to-face learning, which enables teachers to group students flexibly and offers educators rich data on students' progress.

Furthermore, sites such as Khan Academy have brought on-demand explanations of concepts—ranging from addition and subtraction to quasars and galactic collisions—to students' mobile devices. And increasingly, students are accessing virtual simulations that allow them, for example, to take a virtual "walk" through an organic molecule as if it were a building.

The pace at which students are adopting new technologies is extraordinary. A third of the nation's high school students pursue online courses, and millions of people are enrolled in Web-based college classes.

This is exciting stuff, although I do not believe that any single technology will reinvent schooling. Further, I emphatically do not believe that technology ever can replace teachers in any way. The vital human connection between educator and learner will always be the crucial spark in education. Technology, however, can enhance that spark by helping teachers to use their time and talents more effectively and to personalize the learning experience to the needs and interests of individual students.

Over the next few years students will see the tests they take at the end of the year move online, if they haven't already, and the tests will, frankly, get better. These tests will ask students to develop products or experiments; test hypotheses; analyze data; and support, justify and explain their reasoning.

PERSONALIZED LEARNING THROUGH TECHNOLOGY

AMONG THE MOST IMPORTANT directions for technology—and one that the U.S. Department of Education is working to accelerate—is supporting the efforts of teachers to tailor learning to the needs of each student. One of the most enduring, and valid, criticisms of our education system is that it has taken a one-size-fits-all approach to our kids in the face of their unique combinations of gifts and challenges. Personalizing learning is the idea that the pace, approach and context of the learning experience should be tailored to the needs and interests of individuals. It is easy (and common) to tell a teacher to adapt a lesson to the needs of each child, but hard to do it. Technology can help. By blending face-to-face and online learning, teachers can enable students to work at their own pace, be flexible in grouping students according to ability, and get a dynamic stream of information about where students are doing well and where they are struggling.

The Department of Education is taking active steps to support states and school systems that are working to become models for personalized learning. With support from a fund called the Race to the Top–District competition, 55 school districts across 11 states and the District of Columbia are demonstrating how they use technology to personalize education and provide school leaders and teachers with innovative tools.

USING TECHNOLOGY TO IMPROVE ASSESSMENT

OTHER FEDERAL INITIATIVES aim to bring technological innovation to everyone's least favorite part of school: testing. Over the next few years students will see the tests they take at the end of the year move online, if they have not already, and the tests will, frankly, get better. It is vitally important to assess students' learning every year. Without that feedback, schools can fail to identify and help the most vulnerable students. Improved tests will also be critical for supporting the recent efforts by nearly every state to establish new and higher academic standards, including the Common Core standards initiative. The federal government is supporting that state-led effort by providing more than $350 million to two consortia of states that are creating tests to measure student mastery of those standards.

These new assessments will test students' ability to read complex texts and solve real-world problems. They will also provide a better measure of whether students are on track to graduate from high school with the knowledge and skills to succeed in college and the workforce.

One consortium is developing an adaptive test—meaning that the difficulty of questions will change during the course of the exam, based on student answers. This type of assessment has the potential to allow for a more precise understanding of student skills.

Yet these new assessments will require major improvements. Over the coming years everyone interested in changing education will need to push further to find ways to design even better assessments. These tests will ask students to develop products or experiments; test hypotheses; analyze data; and support, justify and explain their reasoning. And over time we will see students work within real-world scenarios to solve problems with assessments that function almost like flight simulators. These tests will examine if students understand content and better gauge whether they can demonstrate critical thinking and apply learning.

Indeed, we are seeing other improvements in testing. This past May, for example, the Advanced Placement (AP) biology exam was updated to improve how it assesses students' critical thinking about scientific issues. The number of multiple-choice questions has been reduced by nearly half, and the number of open-ended questions—requiring students to construct a thoughtful written response—has doubled. In the next two years we will see AP upgrades for chemistry and physics as well.

BREAKING THE DAM: ACCESS TO BROADBAND

WHAT ALL THESE INNOVATIONS in teaching and testing share is a dependence on technology—particularly, reliable, high-speed Internet connections. Yet today fewer than 20 percent of educators say their school's Internet connection meets their teaching needs. In addition, although 91 percent of teachers have access to computers in their classrooms, less than a quarter say they have the right level of technology. Moreover, our teachers do not get enough training and support to integrate technology in their classroom and lessons.

Too often it is schools in low-income and rural communities that are on the wrong end of that connectivity gap. The divide grows even more pronounced when students leave school and go home. Alarmingly, a 2012 report from the Federal Communications Commission reveals that 19 million Americans—especially those in rural areas—do not have access to broadband in their communities at all.

That is why I am so excited about the president's call in June for a five-year effort that will provide high-speed broadband and wireless to 99 percent of students. The ConnectED initiative also aims to improve the skills of teachers, providing every educator in America with support and training to integrate technology into classroom lessons.

The federal government has had a role in bridging the digital divide and ensuring that all students have access to the Internet since 1996, through the FCC's E-Rate program. E-Rate has enabled the percentage of classrooms with Internet connections to increase to more than 95 percent, from 14 percent when it began.

Yet bandwidth has not kept pace with the rapidly increasing demand for classroom technology or high-tech applications that require faster, more reliable Internet connections. Currently far too many schools and districts struggle with slow Internet speeds, inadequate wiring and a lack of hardware. Indeed, the typical school has a slower Internet connection than the typical house in America; a school wired in the early years of E-Rate could be overwhelmed by students in just one classroom trying to stream video. Broadband Internet is the interstate highway for knowledge; ConnectED will build the on-ramps our schools and educators need.

Educators can help right now. Every school and district should take stock of its actual bandwidth capability by using simple tools to test and monitor Internet connection speeds, such as the one provided by SchoolSpeedTest.org. Gathering and submitting this information will clarify our collective understanding of schools' bandwidth needs and provide better data to help districts and states expand capacity.

The deficit of high-speed connectivity is a challenge we must meet. The upside to investing in quality digital infrastructure in schools is huge.

Expanding broadband in every school will mean that students will benefit from higher standards and the assessments that go with them, along with a new generation of learning technologies—without barriers of wealth and geography.

BRIDGING A NEW DIGITAL DIVIDE

BANDWIDTH is only the first challenge we must face in making technology a tool for equity. We also must commit, together, to make new technologies a force that lifts all students. It is no secret that affluent families will use their wealth to put the best learning tools in their kids' hands. And studies have demonstrated that parents in more affluent communities tend to more closely supervise their children's technology use—resulting in greater learning. The troubling possibility is that the digital-learning revolution could thus simply widen the opportunity gap between students who attend poorer and wealthier schools. For technology with such exciting, barrier-breaking possibilities, that would be a tragedy.

It is up to schools, districts, parents and technologists to figure out how to balance this equation—to make sure that teachers, especially in low-income communities, have access to cutting-edge technology and good guidance about how to choose tools that will work well for their students.

Classrooms such as Kristie Ford's in Detroit have demonstrated what is possible. It is up to the rest of us to learn from her.

***Arne Duncan** is U.S. secretary of education.*

MORE TO EXPLORE

Enhancing Teaching and Learning through Educational Data Mining and Learning Analytics: An Issue Brief. U.S. Department of Education, Office of Educational Technology, October 2012.

Emerging Opportunities in K–12 Learning Analytics for Personalized Learning at Scale. Roy Pea. Lecture at Stanford University's mediaX 2013 Conference, January 8, 2013. **www.youtube.com/watch?v=27UW5DKRpOg**

NMC Horizon Report: 2013 K–12 Edition. L. Johnson, S. Adams Becker, M. Cummins, V. Estrada, A. Freeman and H. Ludgate. The New Media Consortium, 2013.

STUDENT POLL

"I WAS PLEASANTLY SURPRISED"

One in five science students surveyed by *Nature* and *Scientific American* has participated in a MOOC—and most would do so again

By Jeffrey Bartholet

Stefan Kühn studies biochemistry at Stellenbosch University in the wine country of South Africa's Western Cape province. He was working on his master's thesis last year and writing in his usual way, which he describes as messy and free-flowing. Then he took a massive open online course (MOOC) from Duke University called Think Again: How to Reason and Argue. It changed the way he approached his thesis. "It taught me what a good argument is, how to construct it, how to avoid general fallacies," Kühn says. "I started the course because of personal interest (I love a lively debate) and was pleasantly surprised when I realized I was using it for my write-ups as well."

Kühn enjoys MOOCs and has recommended them to friends, and in this regard, he is typical of many science, technology, engineering and mathematics (STEM) students who take classes from online platforms. A readers' survey conducted by *Nature* and *Scientific American* found that more than 80 percent of 1,128 STEM students who had taken at least one MOOC agreed or strongly agreed that they enjoyed the latest course they took. Slightly larger percentages said they would take a MOOC in the future and would recommend MOOCs to others.

Kühn is also typical in that he, like a large majority of those surveyed, did not take the course to fulfill any formal qualification. He uses MOOCs to supplement his knowledge and to learn things he cannot find in his brick-and-mortar university. He followed the Duke reasoning course through to the end but also dabbled in other online courses on social modeling and computer programming. Because the lessons cost him nothing—and do not affect his grades or transcript—he is free to jump in and out as he is able to, without necessarily completing all the assignments or quizzes.

Similarly, Yang Liu, a Chinese citizen pursuing Ph.D. studies at Osaka University in Japan, took MOOCs to fill gaps in her knowledge. Although she had earned a master's in biotechnology, Liu is now doing research on tissue engineering, which she had never studied before. "I didn't have sufficient time to take half-year undergraduate lectures or read [more than] 1,000 pages [of] text books," she says. So Liu read the transcripts of a Yale University course in biomedical engineering, absorbed the online lecture notes for the Massachusetts Institute of Technology's Molecular Principles of Biomaterials and watched video lectures related to stem cells from other universities. (The Yale and M.I.T. offerings are part of their respective OpenCourseWare programs, which predate MOOCs.) Because her English is weak, Liu could not catch every point in the video sessions, so she had to review lecture notes at the same time. Even so, Liu says, "MOOCs still saved me a lot of time."

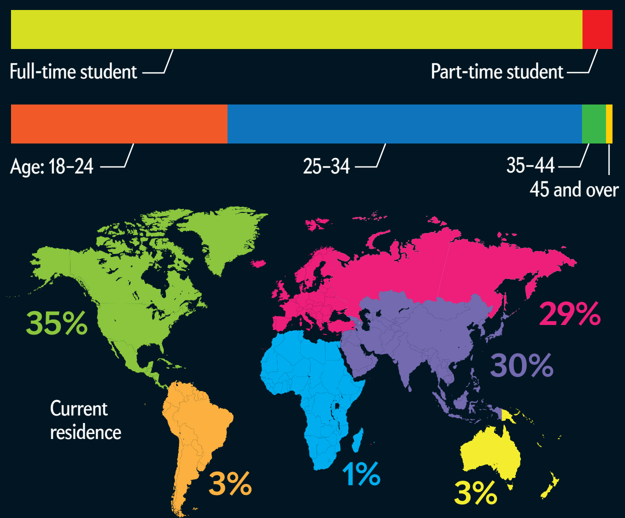
The MOOC students surveyed, nearly half of whom had a biology focus, included skeptics, of course. The number of people who thought traditional courses offered greater educational value than MOOCs was roughly equal to the number who favored the online approach. Yet the percentage of those who thought traditional courses offered superior career value was significantly larger (43 versus 26 percent). Kathleen Nicoll, an associate professor of geography at the University of Utah, took an M.I.T. mathematics class and was underwhelmed. She notes that the course mostly consisted of PowerPoint graphics and canned videos of a professor solving problems. "MOOCs do a good job of basically documenting information," she says. "It's like television—a very passive experience."

Although some classes try to mimic research experiences in a virtual lab, that cannot substitute "for smelling formaldehyde or seeing something almost explode in your face and having to react to that," Nicoll says. She also believes that human interaction is fundamental to learning and that online forums and discussion groups are no substitute. "It's kind of like the difference between having a real friend and a Facebook friend," she says. Yet even Nicoll sees benefits: "One of the huge upsides is that MOOCs can reach everyone [with a computer and Internet]—people who are differently abled, people behind bars in prison."

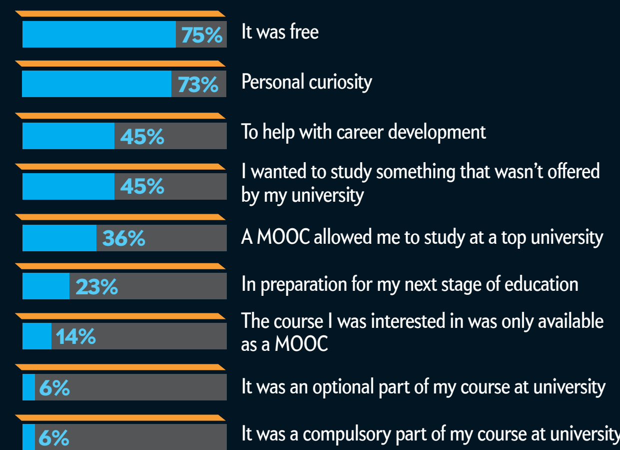
Because failure is cost-free in a MOOC, the basic human tendencies toward procrastination and sloth are stronger than in traditional classes. Still, many STEM students seem motivated to do all or most of the course work, in part to get certificates saying they completed the class. Shannon Bohle, a medical librarian and a blogger at SciLogs.com who has taken eight MOOCs, sometimes "lurks" in online classes, but on several occasions she has been driven to do enough work to earn a "statement of accomplishment." "People always like to have badges and trophies," she says with self-deprecating humor. "I'm doing the courses as a hobby, really—I'm not applying them toward a degree—and I like to share with my friends that I finished the course and hear everyone say, 'Oh, you're so brilliant. Kudos to you!' "

In May, *Scientific American* and *Nature* (which are both part of Nature Publishing Group) surveyed readers about their experiences with MOOCs (massive open online courses) and other digital education tools. We posted a link to the survey on the *Scientific American* and *Nature* Web sites, disseminated it via social media, and e-mailed it to registered users. The graphics below represent the 5,851 responses we received from undergraduate and graduate students around the world who study math and science.

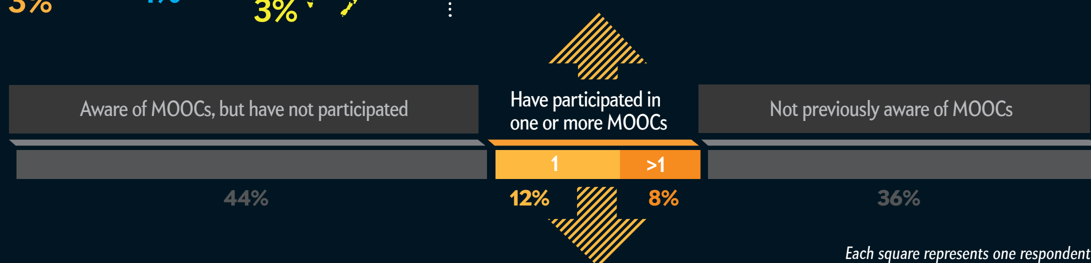
Who Took the Survey



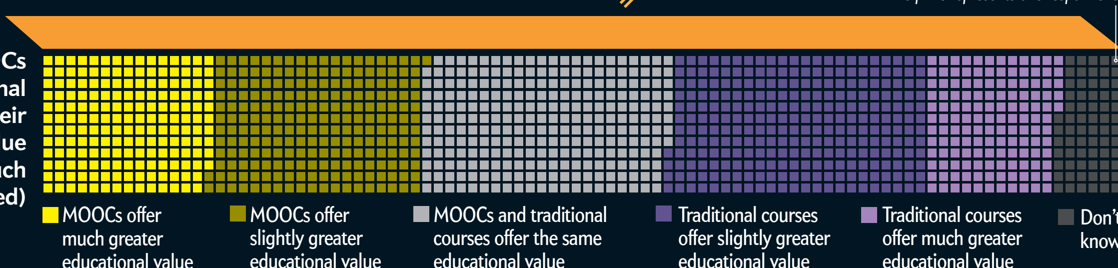
What were your main motivators for taking your most recent MOOC?



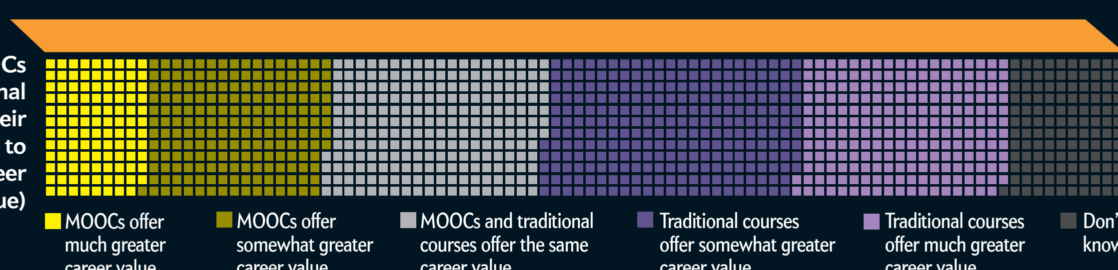
Which of the following best describes your awareness of and participation with MOOCs?



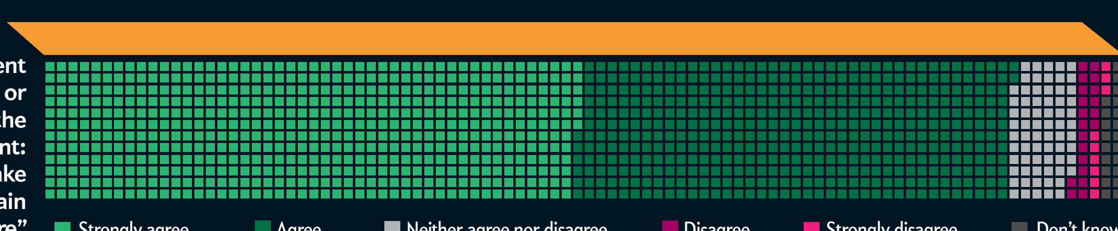
Compare MOOCs with traditional courses for their educational value (i.e., how much you learned)



Compare MOOCs with traditional courses for their perceived value to your future career (i.e., career value)

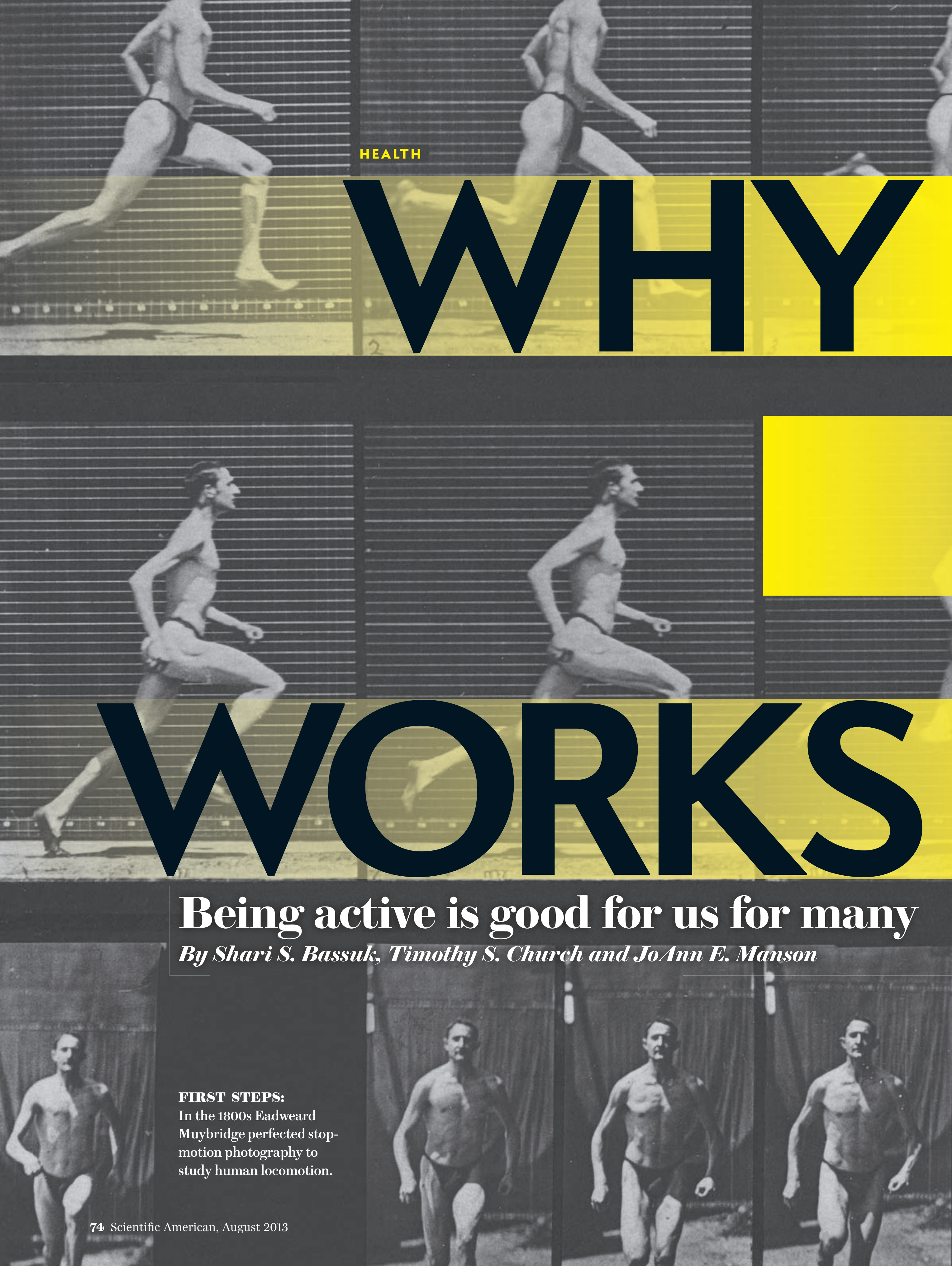


To what extent do you agree or disagree with the following statement: "I would take a MOOC again in the future"



SOURCE: KATIE ALLIN, SURVEY PROJECT MANAGER *Nature Publishing Group*

Graphic by Jen Christiansen



HEALTH

WHY WORKS

Being active is good for us for many

By Shari S. Bassuk, Timothy S. Church and JoAnn E. Manson

FIRST STEPS: In the 1800s Eadweard Muybridge perfected stop-motion photography to study human locomotion.

EXERCISE

reasons beyond the old familiar ones

MAGIC

Shari S. Bassuk is an epidemiologist at Brigham and Women's Hospital and a research associate at Harvard Medical School.

Timothy S. Church is John S. McIlhenny Endowed Chair, director of the Preventive Medicine Research Laboratory and professor at the Pennington Biomedical Research Center at Louisiana State University.

JoAnn E. Manson is chief of the division of preventive medicine at Brigham and Women's Hospital, professor of medicine and Michael and Lee Bell Professor of Women's Health at Harvard Medical School, and professor in the department of epidemiology at the Harvard School of Public Health.

WE ALL KNOW WE SHOULD EXERCISE.

But few realize that being physically active is the single most important thing that most of us can do to improve or maintain our health. Regular movement not only lowers the risk of developing or dying from heart disease, stroke and diabetes, it also prevents certain cancers, improves mood, builds bones, strengthens muscles, expands lung capacity, reduces the risk of falls and fractures, and helps to keep excess weight in check. And those are just some of the more familiar effects.

An explosion in research over the past few years has extended those observations even further. Among other things, exercise appears to boost brainpower—specifically the ability to carry out tasks that require attention, organization and planning, reduce symptoms of depression and anxiety in some people, and enhance the immune system's ability to detect and fend off certain types of cancer. In addition, researchers are moving beyond describing the gross health benefits of regular physical movement to detailing the positive changes that occur at the level of cells and molecules for specific conditions such as atherosclerosis and diabetes.

Studies aimed at tracing the many ways, large and small, that various systems in the human body (cardiovascular, digestive, endocrine and nervous, to name just a few) are affected by exercise show that the benefits most likely result from minor to moderate improvements in many aspects of physiology, as opposed to large favorable effects on a small number of processes in particular cells and tissues.

Investigators have also come to realize that people need not be triathletes to reap exercise's benefits. Twenty years ago preventive health experts focused almost exclusively on the gains to be had from vigorous activity. Today they emphasize the value of sustained bouts of moderate movement as well. One of us (Manson) helped to demonstrate comparable benefits of moderate and vigorous exercise for several health outcomes in the large-scale Nurses' Health Study and the Women's Health Initiative. Based on data from these and other projects, the latest U.S. exercise guidelines (published in 2008) recommend the equivalent of at least 30 minutes of moderate activity, such as brisk walking, five or more days a week (or 75 minutes of vigorous activity, such as jogging, each week), plus 30 minutes of muscle-strengthening activity at least two days a week.

A closer look at some of the most exciting findings offers a

IN BRIEF

Routine physical activity of moderate or vigorous intensity substantially reduces the risk of dying from heart disease, stroke, diabetes, cancer and other ills.

Investigators have recently identified numerous previously unknown ways in which habitual exercise can reduce the risk of heart disease and cancer, can help control diabetes and can even facilitate learning.

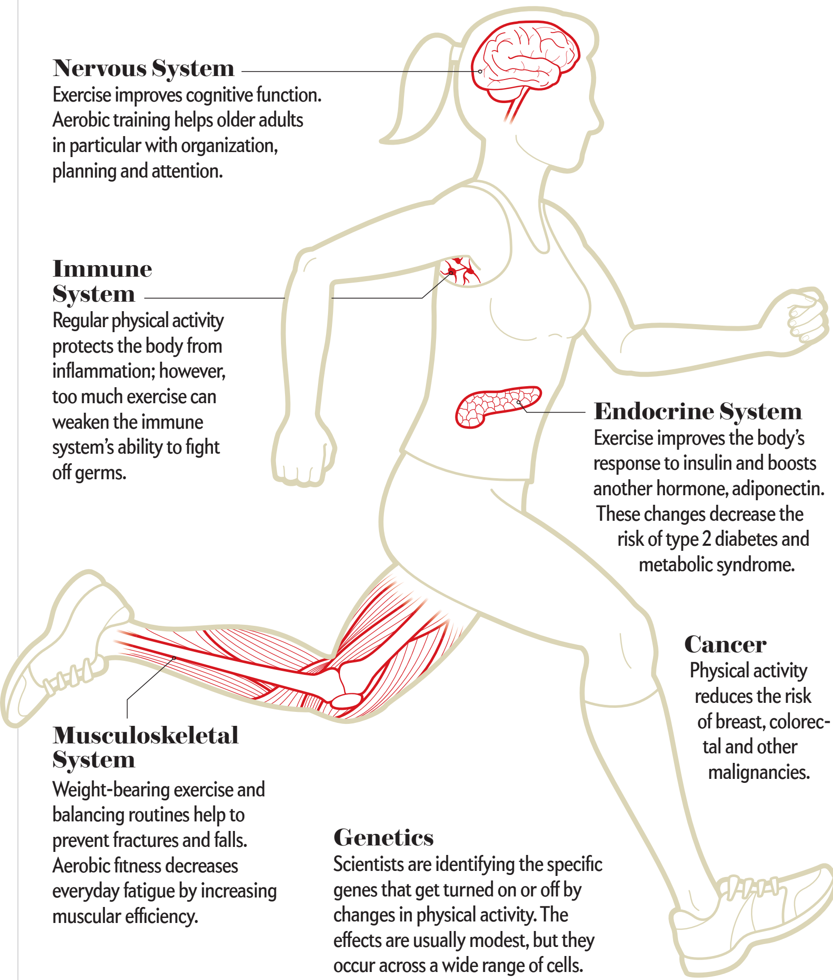
Prolonged sitting may, however, cancel some of the health advantages gained through regular exercise.

PRECEDING PAGES: EADWEARD MUYBRIDGE *University of Pennsylvania Archives*

BEYOND THE HEART AND LUNGS

Exercise Benefits Even Obscure Parts of the Body

Most people do not realize that sustained bouts of moderate to vigorous physical activity completely change our bodies from the inside out. Here is a look at a few of the less widely known effects, starting with the neural connections in the brain and extending all the way out to the major muscles and bones of the limbs.



taste of the less obvious ways that exercise protects our body and keeps it running well.

IMMEDIATE EFFECTS

TO FULLY GRASP the latest findings, it helps to know something about how the body generally responds to increased physical demands. Exercise means different things to different people. From snowshoeing to swimming to a fast walk on the beach, exercise can take many forms and occur at differing levels of intensity. Aerobic exercise is the type that significantly boosts the amount of oxygen needed by the muscles, requiring the lungs to work harder. Its health benefits are also the best understood. But more stationary forms of exercise—such as lifting weights or practicing one's balance—also have their place.

Scientists have developed fairly rigorous methods for measuring the intensity of aerobic exercise in research laboratories. An effective and much less expensive way to measure how much you are pushing your body outside the lab is the talk test. Moderate activity begins when your heart starts beating faster and you are breathing more heavily. You are still at a moderate level if you can talk or recite a poem while you are moving. If you can croak out only a word or two at a time, then you are exercising vigorously. At the other end of the scale, if you can sing while moving, then you are working at a light level of intensity.

Whenever a person picks up the pace, the nervous system prepares all the body's organs for action. Initially the individual may notice a heightened sense of awareness, increased heart rate, quickened breathing and light sweating. Internally, blood flow is reduced to those organs, such as the gastrointestinal tract and kidneys, that are not essential for movement. At the same time, blood vessels in the active muscles open up, ensuring that enough oxygen-rich blood flows to those muscles that are working the most.

Once in the muscle cells, oxygen diffuses into cellular structures called mitochondria, which use it to generate energy for the cell. The basic fuel for this process is the sugar molecule glucose, which the body creates through the breakdown of larger food particles and absorbs during the course of digestion. The addition of oxygen to glucose in mitochondria triggers a highly efficient kind of combustion. When oxygen is available, mitochondria can create nearly 20 times more energy per glucose molecule than they can in the absence of oxygen.

The body first burns up glucose molecules that are stored in the form of a compound called glycogen, found primarily in the liver and muscles. But as exercise continues, the available stock of glycogen is depleted and molecules of triglyceride (which is a kind of fat) become the chief source of fuel. All this internal combustion produces certain by-products, such as lactic acid and carbon dioxide, which seep from the muscles into the bloodstream, where they are sensed by the rest of the body. The increasing concentration of these wastes prompts further biochemical reactions in the brain, lungs and heart that eventually make removal of these compounds more efficient and less tiring.

The benefits of exercise really start to accumulate once physical activity becomes a routine habit. The body adapts to the increasing demands being placed on it, leading to increased stamina as individuals become more fit. For instance, the lungs

Illustration by Brown Bird Design

process more oxygen as each breath becomes deeper and the heart pumps more blood with each beat. These adaptations, which typically begin to show up within a few weeks of meeting or exceeding the federal guidelines on physical activity, also lead to changes in biology that improve long-term health.

MOLECULAR CHANGES

ENTIRE LIBRARIES could be packed with data demonstrating the effects of exercise on everything from major organ systems to how various genes are turned on or off. A few top-level conclusions are outlined in the infographic that accompanies this article [*see box on preceding page*]. But we will focus here on some of the newly discovered mechanisms that help to explain why exercise expands our cognitive capacities, improves our ability to control blood glucose levels and strengthens our cardiovascular system. These changes have a greater effect on the quality of daily life than almost any other exercise benefits.

Athletes have long known that exercise boosts their mood and mental health. And yet it was not until 2008 that scientists were able to directly measure the so-called runner's high—a sense of euphoria that occurs after prolonged exercise. Not only did they show that the brain released more endorphins (opioid-like hormones that evoke pleasurable feelings) during a long-distance run, they also determined that the compounds were active in regions of the brain responsible for strong emotions. (Previous work had detected an endorphin surge only in the bloodstream, which was unrelated to changes in the brain.)

Regular prolonged movement—at whatever intensity level can be safely managed—should be built into everyone's daily habits and physical environment.

More recently, investigators have focused on the chemical changes in the brain by which exercise enhances our ability to concentrate, think and make decisions. In 2011 a scientifically rigorous experiment—known as a randomized controlled trial—of 120 people in their 60s and 70s demonstrated that exercise increases the size of a part of the brain called the hippocampus. The study's authors noted that the specific portion of the hippocampus that was affected by exercise is one that allows people to remember familiar surroundings; it is also one of the few areas of the brain that makes new nerve cells—at least in rats. Newborn neurons are thought to help with distinguishing similar but different events and things. Animal studies have further shown that exercise increases the levels of the chemical responsible for triggering the growth of these new neurons—a molecule known as brain-derived neurotrophic factor, or BDNF.

Now research is challenging what we thought we knew about how exercise prevents heart disease. Scientists initially believed that routine activity reduced cardiovascular risk largely by decreasing blood pressure and lowering the amount of LDL cholesterol (also known as the bad cholesterol) while raising the amount of HDL cholesterol (the good cholesterol) in the blood. This conclusion was only partly correct. Exercise does in fact lower blood pressure substantially for some individuals, but for most people this benefit of exercise is relatively small. Moreover, exercise—particularly resistance exercise, such as weight training—can raise HDL cholesterol, a change that typically takes several months to emerge, although the effect is fairly modest—on the order of a few percentage points.

Further investigation has shown that the more important LDL-related effect has to do with how exercise changes the molecule's properties as opposed to reducing the amount found in the blood. Technically speaking, LDL is not synonymous with cholesterol; rather it carries cholesterol through the bloodstream the way a delivery truck carries groceries. (Being made of fat, cholesterol cannot dissolve in the watery environment of the bloodstream, so it has to be packaged in something that can.) LDL particles also come in various sizes in the same way that groceries can be delivered in minivans or giant trucks.

Over the past several years a growing number of scientists have found that smaller LDL molecules are particularly dangerous. They have a tendency, for example, to lose electrons, which then ricochet around the blood vessels damaging other molecules and cells (think crazed driver behind the wheel of a beat-up van). Large LDL molecules, on the other hand, are much more stable and float through the bloodstream without crashing into anything (more akin to big, well-maintained trucks with professional drivers).

Studies now show that exercise increases the number of larger, safer LDL molecules while decreasing the number of small, dangerous ones, and it alters the ratio by boosting the activity of an enzyme called lipoprotein lipase in fat and muscle tissue. Two people with the same amount of cholesterol in their blood but different levels of physical activity could thus have very different risk profiles for cardiac disease. The couch potato would probably have a lot of small LDLs and very few if any large ones, whereas large LDL molecules would predominate in the active person's blood. And yet despite having an identical cholesterol level, the first person would have several times the risk of suffering a heart attack of the second person.

Regular physical activity positively affects another key component of the blood—the sugar glucose. The liver, pancreas and the skeletal muscles—which move your head, arms, legs and torso—normally work together seamlessly to make sure that each part of the body gets the sugar it needs, whether you are at rest or active. By definition, exercise places increased demands on the skeletal muscles, which need increasing amounts of glucose to fuel their efforts. Over the long term, exercise also prompts the fibers within the muscle to become more efficient at using glucose, which allows it to become stronger.

The liver responds immediately to the call for more fuel by churning sugar molecules into the bloodstream, and the pancreas releases a hormone called insulin that signals the cells to draw increasing amounts of glucose out of the blood. You might imagine that the whole process could lead to wild swings in glucose levels especially after a meal or a run, but the body works hard to keep its blood sugar levels within a fairly limited range of between

70 and about 140 milligrams per deciliter (and well below 126 mg/dL in the fasting state)—at least in folks who do not have diabetes. One reason that blood sugar needs to stay above 70 mg/dL is that the brain depends heavily on glucose as its primary source of fuel and thus is acutely sensitive to any change in the amount found in the blood. Although extremely low glucose levels can lead to coma and death in a matter of minutes, it is just as important from a physiological point not to spend long periods at the high end of the scale. Broadly speaking, extra sugar in the blood tends to gum up the works, causing cells to age prematurely.

As exercise becomes more of a daily habit, the muscles grow more sensitive to the effects of insulin. That means the pancreas does not have to work as hard to help keep glucose levels in check; lower levels of insulin will accomplish the same result as higher amounts once did. Doing more with less insulin is particularly helpful for people with type 2 diabetes, whose bodies have trouble keeping blood sugar in the normal range, in large part because they have become resistant to the hormone's effects. But insulin also promotes the proliferation, or rapid production, of new cells—and as such, elevated levels have been linked to a greater risk for developing breast and colon cancer in particular.

Recently physical activity has also been shown to promote the uptake of glucose through another pathway that does not require the presence of insulin. Having a second pathway to get glucose out of the bloodstream and into the muscle cells could open up new directions in the treatment of diabetes.

Intriguingly, the greatest benefits for people with diabetes seem to come from mixing different types of exercise. Two large randomized clinical trials have reported the combination of aerobic and resistance exercise is better at controlling blood glucose levels than either type of exercise alone. The first study was conducted in such a way, however, that it was unclear if the benefit came from the combination of exercise types or the fact that participants who underwent aerobic and resistance training also ended up exercising longer than their counterparts who followed a single exercise program. One of us (Church) decided to tackle that question by leading a second trial in which 262 previously sedentary men and women with diabetes were divided into four groups: an aerobic exercise group (who walked on a treadmill), a resistance group (seated rowing, leg presses, and the like), a combination group, and the control group, which undertook weekly stretching and relaxation classes.

Each of the groups who engaged in physical activity expended the same amount of time and effort (approximately 140 minutes per week) over the course of nine months. They also all lost inches off their waist, and both groups that performed aerobic exercise became more fit. But only the group that undertook both resistance and aerobic exercises exhibited a significant drop in their blood in the amount of a protein called HbA1c, which acts as an indicator of average blood sugar level over the past several months. The additive benefit suggests that aerobic and resistance training operate through different physiological mechanisms—an idea that investigators at Pennington Biomedical Research Center in Baton Rouge, La., and elsewhere are actively pursuing.

Another way that continued exercise strengthens muscles is by boosting the formation of energy-producing mitochondria. In response to regular exercise, muscle cells start making a protein called PGC-1α, which directs the cells to churn out new mitochondria. More mitochondria mean each cell can convert more glucose into energy, increasing the strength and resistance to fatigue of the whole muscle.

SITTING HAZARD

GIVEN THE MULTIPLE health benefits of moderate exercise, you might expect that everyone is lacing up their walking shoes and heading out the door. But many Americans fail to achieve even the recommended half an hour of moderate activity on five or more days of the week. Only 52 percent of U.S. adults are active enough to meet the aerobic exercise guideline, and 29 percent strengthen their muscles as recommended twice a week for 30 minutes at a time. One in five Americans meets the recommendations for both aerobic and resistance exercise.

The difficulties of changing people's sedentary habits have prompted scientists to investigate whether lighter or shorter bouts of exercise have any health benefits. Positive results, they hope, might motivate even couch potatoes to start moving more than they are used to doing. So far the data suggest that even minimal daily exercise routines can extend people's lives somewhat. A 2012 analysis of the data from six studies, totaling 655,000 adults in the U.S. who were tracked for about 10 years, found that people who expended as little as 11 minutes per day on leisurely activities (gardening, washing the car, taking an evening stroll) had a 1.8-year longer life expectancy after age 40 compared with their inactive peers. Admittedly, participants who met recommended guidelines for moderate activity were better off; their life expectancy was 3.4 years longer. And those who were active between 60 and 90 minutes each day achieved even greater gains (4.2 years longer life expectancy).

Despite the advantages of minimal efforts, a comprehensive look at exercise studies to date shows that most people would benefit from ramping up their activity—for example, adding moderate activity if they are light exercisers or short bursts of vigorous activity if they are moderate exercisers. Perhaps the worst news for today's office-bound knowledge workers is that sitting for more than six hours a day during leisure time may prove harmful even if you also manage a few high-intensity workouts. Still unknown: whether it is something about sitting itself that is a problem or the lack of movement usually associated with it.

Given the continual and growing evidence for the health benefits of physical activity, the message is clear. Regular prolonged movement—at whatever intensity level can be safely managed—needs to be built into everyone's daily habits and physical environments. It should become as easy as jumping into a car is now.

We strongly recommend that doctors and other health care providers regularly write a prescription for exercise during routine office visits. In addition, we advocate for increased research into the kinds of behavioral programs, public health campaigns and changes in urban design that will facilitate sustained levels of beneficial physical activity in our largely sedentary society. SA

MORE TO EXPLORE

Global Recommendations on Physical Activity for Health. World Health Organization, 2010. http://whqlibdoc.who.int/publications/2010/9789241599979_eng.pdf

Physical Activity Guidelines for Americans: www.health.gov/paguidelines

SCIENTIFIC AMERICAN ONLINE
See how your activity level stacks up against national standards at ScientificAmerican.com/aug2013/fitness-test

Barbie Latza Nadeau, an American journalist, is the Rome bureau chief for *Newsweek* and The Daily Beast and is working on a novel based on the *Costa Concordia* disaster.

ENGINEERING

Raising the Wreck

The smallest mistake in refloating the crippled *Costa Concordia* cruise ship will sink it, creating an environmental disaster

By Barbie Latza Nadeau

EIGHTEEN MONTHS AGO the massive *Costa Concordia* cruise liner crashed onto the tiny island of Giglio, 12 miles off Italy's western coast. Within minutes the 950-foot vessel tipped sideways, tossing passengers into the sea. In the end, 32 people died and 64 were seriously injured.

In the very near future, engineers will attempt to pull the battered ship upright and float it away. The hulk is snagged on jagged outcroppings of rock in 60 feet of water, groaning and swaying precariously with each incoming wave on the edge of a steep slope that drops 200 feet to the bottom of the sea. If the operation goes well, it will be the greatest success in the history of maritime salvage. But if a single thing goes wrong, the boat will tear apart or sink whole, seriously polluting the Pelagos Sanctuary for Mediterranean Marine Mammals—the largest park of its kind in Europe—which surrounds Giglio. The waters are a haven for dolphins, porpoises, whale calves and scores of other sea creatures. Exquisite coral reefs line the seafloor immediately below the stranded, rusting ship.

Although reclaimers siphoned the fuel from *Concordia*'s tanks, the six mammoth Wärtsilä engines still hold volumes of diesel fuel and oily lubricants, as does the engine room, all of which would be released into the pristine waters if the ship went down. So would thousands of gallons of chemicals, from cleaning supplies to paints, each container burst by water pressure. And the vessel was stocked to feed 4,229 people for 10 days when it left port just three hours before it sank, much of the food inside freezers that would decompose. Tons and tons of ship metal would leach and corrode.

Shipwrecks this big are usually blown up or sunk. But Italy's environmental ministry backed the people of Giglio in pressuring Costa Cruises to right the vessel and float it to the mainland, to preserve the island's pristine shore and waters. Also, once the boat is recovered, police will investigate its watery innards—a crime scene that may hold evidence against Captain Francesco Schettino, who is charged with manslaughter and abandoning ship. Two bodies have still not been recovered. After the investigation, the hulk will be disassembled.

The recovery operation falls to a charismatic, 51-year-old freelance salvage master from South Africa named Nick Sloane, well known in the industry and not exactly averse to risk. Hired by the two companies that have the recovery contract—Florida-based Titan Salvage and Italian firm Micoperi—Sloane has worked on some of the largest maritime accidents in the world. He has a file of photographs on his iPhone depicting all the ships he has detonated in his long career.

This time, however, no explosives will be involved. Sloane and his team will employ a procedure known as parbuckling. Cables and pulleys will slowly tug the colossal vessel off the rocks and set it upright [*see illustrations on next two pages*]. As the ship becomes vertical, it will land on six massive underwater platforms made of more steel than was used to build the Eiffel Tower. Sloane estimates that the pulling process will take eight hours, during which time his crew will have control up to a certain point. "Then gravity will take over," he says. "If we've done this right, the ship will right herself and rest on the platforms."

If they have not done it right, the platforms may break, and the ship will scrape its way down the underwater slope, shredding and crushing the corals and sea grasses as it slides into the depths. The other danger is that the 114,000-metric-ton ship will come apart under its own weight as it is pulled upright, spilling its toxic contents into the fragile aquatic ecosystem, which has already suffered immensely from the noise and pollution of the salvage operation. "The exterior of the ship was not built to be lifted like this," Sloane says. "When she is lifted, you will hear the twisting and breaking apart of her inner section, but hopefully the outer shell will stay intact." His crew has spent months reinforcing that shell. "Nothing like this has ever been attempted before," Sloane told SCIENTIFIC AMERICAN on a private tour around the wreck and the salvage rigs. "But the more you plan and prepare, the luckier you get."

Even if Sloane succeeds, the work will not be over. The salvage contract demands that the environment be returned to its original state. The large steel platforms will have to be removed, and every hole drilled into the sandy floor for pillars that hold the platform will have to be filled. Sloane wanted to leave the structures in place as a site for a salvage school. But the people of Giglio do not want any trace of the accident to remain as a reminder of the day their idyllic island was marred. SA

LAURA LEZZA *Getty Images*

SALVAGE BOATS siphon diesel fuel from partially submerged tanks on the stricken *Costa Concordia* after the ship crashed onto Italy's Giglio island.

IN BRIEF

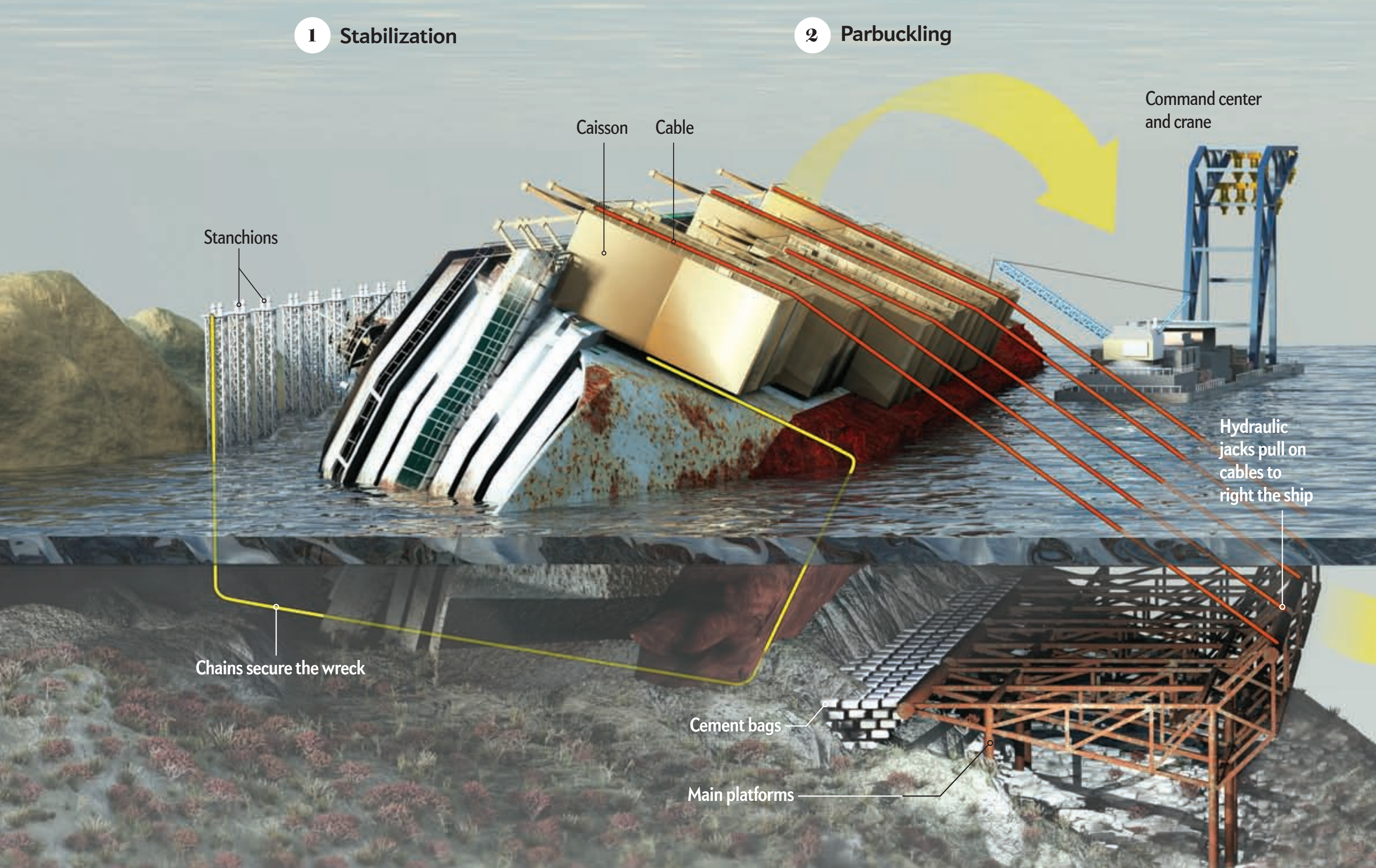
The marooned Italian cruise ship *Costa Concordia* is supposed to be pulled off the rocks of the tiny island of Giglio and floated away, during a tense procedure called parbuckling.

If the process succeeds, it will be the greatest maritime salvage ever. But if one thing goes wrong, the huge vessel will crumble or sink, crushing the coral reef and pouring its toxic contents into the surrounding Pelagos Sanctuary for Mediterranean Marine Mammals.

SALVAGE PLAN

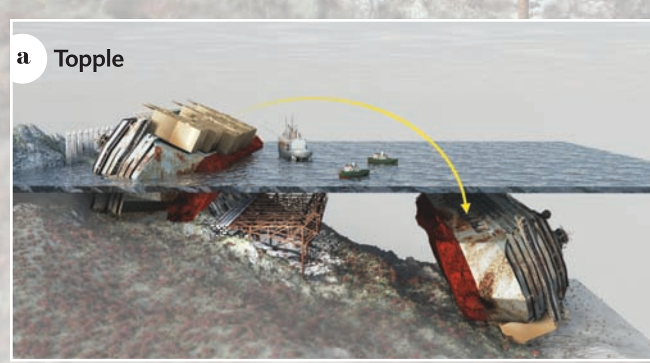
Flip the Ship and Float It Away

The 950-foot *Costa Concordia* is impaled on two large, underwater rock outcroppings. To remove the ship in one piece, it has to be freed and righted. Salvage crews first drove stanchions into the shore and wrapped the ship in chains to prevent it from slipping down the steep seabed and sinking 1. Workers then anchored six massive steel platforms into the granite seabed to give the boat a place to land and laid thousands of cement-filled bags to level the uneven, rock seafloor. They also reinforced the exposed hull so it would not break apart, then attached caissons—hollow boxes 100 feet tall, filled with water and air—that will help float the boat after it is slowly rolled upright during an eight-hour procedure called parbuckling 2. To tip the ship, hydraulic jacks will pull on cables connecting the top of the caissons to the platforms, while tension in the chains will add some control. A giant crane, housing the salvage master's command center, will help lift and stabilize the ship if needed. Microphones and video cameras installed inside the rusting hulk will reveal if and how the innards are shredding. Welders will reinforce the mangled side, then attach caissons there 3. Water in the caissons will slowly be pumped out, raising the ship until it floats, so it can be towed away 4.



What Could Possibly Go Wrong?

The crippled ship is perched precariously above a steeply sloping seafloor that is home to pristine coral reefs, sea grasses and spawning grounds. Any error during the parbuckling procedure could spell disaster. If the ship is pulled too hard, it could topple over the platform and tumble down the ridge a. If the platforms crumple under the weight, the boat could slide down instead b. Either way, a large area of corals and grasses would be crushed and torn. The heavily damaged hull could also break apart under its own weight as it is lifted c, tumbling down the slope in pieces and spilling its toxic guts into the coastal waters. In all three cases, the sunken ship and its contents would rust and rot, contaminating the fragile aquatic ecosystem for years.

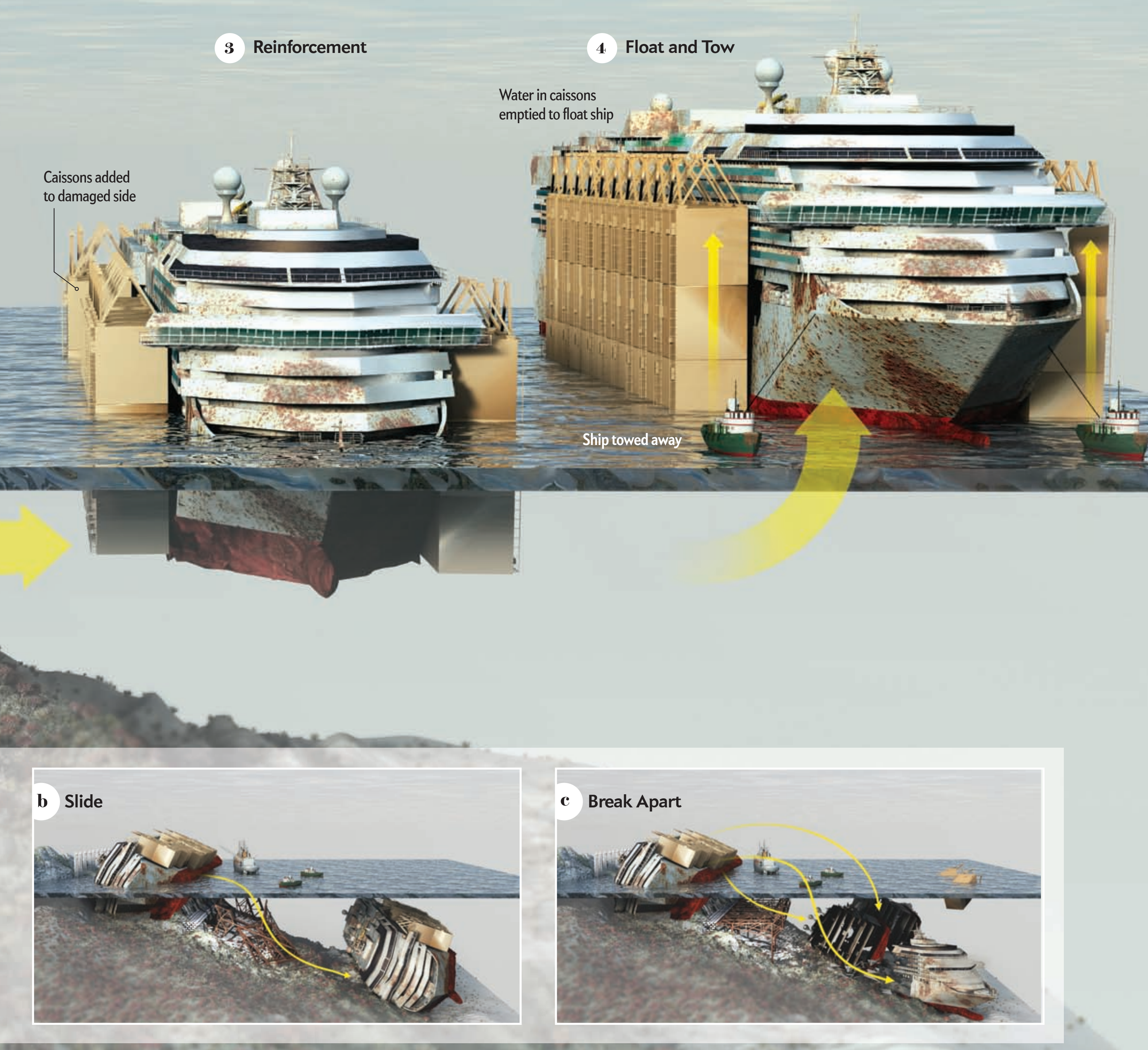


Illustrations by Don Foley

MORE TO EXPLORE

Parbuckling Project (official salvage Web site): www.theparbucklingproject.com
Giglio News (port Web cam): http://bit.ly/nzjyqK
Pelagos Sanctuary: www.tethys.org/sanctuary.htm

SCIENTIFIC AMERICAN ONLINE
For a full account of the *Costa Concordia*'s effects on the residents of Giglio, see ScientificAmerican.com/aug2013/concordia



EVOLUTION

THE SURPRISING ORIGINS OF LIFE'S COMPLEXITY

Scientists are exploring how organisms can evolve elaborate structures without Darwinian selection

By Carl Zimmer

Illustration by Cherie Sinnen

LAB-RAISED fruit flies are more complex than wild ones because their sheltered environment allows even disadvantageous mutations to spread. This artist's conception contrasts typical wild fly anatomy (*left*) with representative mutations that arise in lab flies (*right*).

Carl Zimmer is a *New York Times* columnist and has written numerous books, including *Evolution: Making Sense of Life,* co-authored with Douglas J. Emlen.

CHARLES DARWIN WAS NOT YET 30 WHEN HE GOT the basic idea for the theory of evolution. But it wasn't until he turned 50 that he presented his argument to the world. He spent those two decades methodically compiling evidence for his theory and coming up with responses to every skeptical counterargument he could think of. And the counterargument he anticipated most of all was that the gradual evolutionary process he envisioned could not produce certain complex structures.

Consider the human eye. It is made up of many parts—a retina, a lens, muscles, jelly, and so on—all of which must interact for sight to occur. Damage one part—detach the retina, for instance—and blindness can follow. In fact, the eye functions only if the parts are of the right size and shape to work with one another. If Darwin was right, then the complex eye had evolved from simple precursors. In *On the Origin of Species,* Darwin wrote that this idea "seems, I freely confess, absurd in the highest possible degree."

But Darwin could nonetheless see a path to the evolution of complexity. In each generation, individuals varied in their traits. Some variations increased their survival and allowed them to have more offspring. Over generations those advantageous variations would become more common—would, in a word, be "selected." As new variations emerged and spread, they could gradually tinker with anatomy, producing complex structures.

The human eye, Darwin argued, could have evolved from a simple light-catching patch of tissue of the kind that animals such as flatworms grow today. Natural selection could have turned the patch into a cup that could detect the direction of the light. Then, some added feature would work with the cup to further improve vision, better adapting an organism to its surroundings, and so this intermediate precursor of an eye would be passed down to future generations. And, step-by-step, natural selection could drive this transformation to increased complexity because each intermediate form would provide an advantage over what came before.

Darwin's musings on the origin of complexity have found support in modern biology. Today biologists can probe the eye and other organs in detail at the molecular level, where they find immensely complex proteins joining together to make structures that bear a striking resemblance to portals, conveyor belts and motors. Such intricate systems of proteins can evolve from simpler ones, with natural selection favoring the intermediates along the way.

But recently some scientists and philosophers have suggested that complexity can arise through other routes. Some argue that life has a built-in tendency to become more complex over time. Others maintain that as random mutations arise, complexity emerges as a side effect, even without natural selection to help it along. Complexity, they say, is not purely the result of millions of years of fine-tuning through natural selection—the process that Richard Dawkins famously dubbed "the blind watchmaker." To some extent, it just happens.

A SUM OF VARIED PARTS

BIOLOGISTS AND PHILOSOPHERS HAVE pondered the evolution of complexity for decades, but according to Daniel W. McShea, a paleobi-

IN BRIEF

Conventional wisdom holds that complex structures evolve from simpler ones, step-by-step, through a gradual evolutionary process, with Darwinian selection favoring intermediate forms along the way.

But recently some scholars have proposed that complexity can arise by other means—as a side effect, for instance—even without natural selection to promote it.

Studies suggest that random mutations that individually have no effect on an organism can fuel the emergence of complexity in a process known as constructive neutral evolution.

ologist at Duke University, they have been hobbled by vague definitions. “It’s not just that they don’t know how to put a number on it. They don’t know what they mean by the word,” McShea says.

McShea has been contemplating this question for years, working closely with Robert N. Brandon, also at Duke. McShea and Brandon suggest that we look not only at the sheer number of parts making up living things but at the types of parts. Our bodies are made of 10 trillion cells. If they were all of one type, we would be featureless heaps of protoplasm. Instead we have muscle cells, red blood cells, skin cells, and so on. Even a single organ can have many different cell types. The retina, for example, has about 60 different kinds of neurons, each with a distinct task. By this measure, we can say that we humans are, indeed, more complex than an animal such as a sponge, which has perhaps only six cell types.

One advantage of this definition is that you can measure complexity in many ways. Our skeletons have different types of bones, for example, each with a distinctive shape. Even the spine is made up of different types of parts, from the vertebrae in the neck that hold up our head to the ones that support our rib cage.

In their 2010 book *Biology’s First Law,* McShea and Brandon outlined a way that complexity defined in this way could arise. They argued that a bunch of parts that start out more or less the same should differentiate over time. Whenever organisms reproduce, one or more of their genes may mutate. And sometimes these mutations give rise to more types of parts. Once an organism has more parts, those units have an opportunity to become different. After a gene is accidentally copied, the duplicate may pick up mutations that the original does not share. Thus, if you start with a set of identical parts, according to McShea and Brandon, they will tend to become increasingly different from one another. In other words, the organism’s complexity will increase.

As complexity arises, it may help an organism survive better or have more offspring. If so, it will be favored by natural selection and spread through the population. Mammals, for example, smell by binding odor molecules to receptors on nerve endings in their nose. These receptor genes have repeatedly duplicated over millions of years. The new copies mutate, allowing mammals to smell a wider range of aromas. Animals that rely heavily on their nose, such as mice and dogs, have more than 1,000 of these receptor genes. On the other hand, complexity can be a burden. Mutations can change the shape of a neck vertebra, for instance, making it hard for the head to turn. Natural selection will keep these mutations from spreading through populations. That is, organisms born with those traits will tend to die before reproducing, thus taking the deleterious traits out of circulation when they go. In these cases, natural selection works against complexity.

Unlike standard evolutionary theory, McShea and Brandon see complexity increasing even in the absence of natural selection. This statement is, they maintain, a fundamental law of biology—perhaps its only one. They have dubbed it the zero-force evolutionary law.

THE FRUIT-FLY TEST

RECENTLY McSHEA AND LEONORE FLEMING, a graduate student at Duke, put the zero-force evolutionary law to the test. The subjects were *Drosophila* flies. For more than a century scientists have reared stocks of the flies to use in experiments. In their laboratory homes, the flies have led a pampered life, provided with

Some of the insects had irregular legs. Others acquired complicated patterns of colors on their wings. The segments of their antennae took on different shapes. Freed from natural selection, flies have reveled in complexity.

a constant supply of food and a steady, warm climate. Their wild relatives, meanwhile, have to contend with starvation, predators, cold and heat. Natural selection is strong among the wild flies, eliminating mutations that make flies unable to cope with their many challenges. In the sheltered environment of the labs, in contrast, natural selection is feeble.

The zero-force evolutionary law makes a clear prediction: over the past century the lab flies should have been less subject to the elimination of disadvantageous mutations and thus should have become more complex than the wild ones.

Fleming and McShea examined the scientific literature for 916 laboratory lines of flies. They made many different measures of complexity in each population. In the journal *Evolution & Development,* they recently reported that the lab flies were indeed more complex than wild ones. Some of the insects had irregular legs. Others acquired complicated patterns of colors on their wings. The segments of their antennae took on different shapes. Freed from natural selection, flies have reveled in complexity, just as the law predicts.

Although some biologists have endorsed the zero-force evolutionary law, Douglas Erwin, a leading paleontologist at the Smithsonian National Museum of Natural History, thinks it has some serious flaws. “One of its basic assumptions fails,” he argues. According to the law, complexity may increase in the absence of selection. But that would be true only if organisms could actually exist beyond the influence of selection. In the real world, even when they are pampered by the most doting of scientists, Erwin contends, selection still exerts a force. For an animal such as a fly to develop properly, hundreds of genes have to interact in an elaborate choreography, turning one cell into many, giving rise to different organs, and so on. Mutations may disrupt that choreography, preventing the flies from becoming viable adults.

HUMAN EYE is an organ whose complexity evolved in the classic manner—gradually, with natural selection favoring intermediate forms along the way. But studies of fruit flies and other organisms indicate that complexity may also emerge by other means.

SUREN MANVELYAN

An organism can exist without external selection—without the environment determining who wins and loses in the evolutionary race—but it will still be subject to internal selection, which takes place within organisms. In their new study, McShea and Fleming do not provide evidence for the zero-force evolutionary law, according to Erwin, "because they only consider adult variants." The researchers did not look at the mutants that died from developmental disorders before reaching maturity, despite being cared for by scientists.

Another objection Erwin and other critics have raised is that McShea and Brandon's version of complexity does not jibe with how most people define the term. After all, an eye does not just have many different parts. Those parts also carry out a task together, and each one has a particular job to do. But McShea and Brandon argue that the kind of complexity that they are examining could lead to complexity of other sorts. "The kind of complexity that we're seeing in this *Drosophila* population is the foundation for really interesting stuff that selection could get hold of" to build complex structures that function to aid survival, McShea says.

MOLECULAR COMPLEXITY

AS A PALEOBIOLOGIST, McShea is accustomed to thinking about the kind of complexity he can see in fossils—bones fitting together into a skeleton, for example. But in recent years a number of molecular biologists have independently begun to think much as he does about how complexity emerges.

In the 1990s a group of Canadian biologists started to ponder the fact that mutations often have no effect on an organism at all. These mutations are, in the jargon of evolutionary biology, neutral. The scientists, including Michael Gray of Dalhousie University in Halifax, proposed that the mutations could give rise to complex structures without going through a series of intermediates that are each selected for their help in adapting an organism to its environment. They dubbed this process "constructive neutral evolution."

Gray has been encouraged by some recent studies that provide compelling evidence for constructive neutral evolution. One of the leaders in this research is Joe Thornton of the University of Oregon. He and his colleagues have found what appears to be an example in the cells of fungi. In fungi, such as a portobello mushroom, cells have to move atoms from one place to another to stay alive. One of the ways they do so is with molecular pumps called vacuolar ATPase complexes. A spinning ring of proteins shuttles atoms from one side of a membrane in the fungus to another. This ring is clearly a complex structure. It contains six protein molecules. Four of the molecules consist of the protein known as Vma3. The fifth is Vma11 and the sixth Vma16. All three types of protein are essential for the ring to spin.

To find out how this complex structure evolved, Thornton and his colleagues compared the proteins with related versions in other organisms, such as animals. (Fungi and animals share a common ancestor that lived around a billion years ago.)

In animals, the vacuolar ATPase complexes also have spinning rings made of six proteins. But those rings are different in one crucial way: instead of having three types of proteins in their rings, they have only two. Each animal ring is made up of five copies of Vma3 and one of Vma16. They have no Vma11. By McShea and Brandon's definition of complexity, fungi are more complex than animals—at least when it comes to their vacuolar ATPase complexes.

The scientists looked closely at the genes encoding the ring proteins. Vma11, the ring protein unique to fungi, turns out to be a close relative of the Vma3 in both animals and fungi. The genes for Vma3 and Vma11 must therefore share a common ancestry. Thornton and his colleagues concluded that early in the evolution of fungi, an ancestral gene for ring proteins was accidentally duplicated. Those two copies then evolved into Vma3 and Vma11.

By comparing the differences in the genes for Vma3 and Vma11, Thornton and his colleagues reconstructed the ancestral gene from which they both evolved. They then used that DNA sequence to create a corresponding protein—in effect, resurrecting an 800-million-year-old protein. The scientists called this protein Anc.3-11—short for *anc*estor of Vma*3* and Vma*11*. They wondered how the protein ring functioned with this ancestral protein. To find out, they inserted the gene for Anc.3-11 into the DNA of yeast. They also shut down its descendant genes, Vma3 and Vma11. Normally, shutting down the genes for the Vma3 and Vma11 proteins would be fatal because the yeast could no longer make their rings. But Thornton and his co-workers found that the yeast could survive with Anc.3-11 instead. It combined Anc.3-11 with Vma16 to make fully functional rings.

Experiments such as this one allowed the scientists to formulate a hypothesis for how the fungal ring became more complex. Fungi started out with rings made from only two proteins—the same ones found in animals like us. The proteins were versatile, able to bind to themselves or to their partners, joining up to proteins either on their right or on their left. Later the gene for Anc.3-11 duplicated into Vma3 and Vma11. These new proteins kept doing what the old ones had done: they assembled into rings for pumps. But over millions of generations of fungi, they began to mutate. Some of those mutations took away some of their versatility. Vma11, for example, lost the ability to bind to Vma3 on its clockwise side. Vma3 lost the ability to bind to Vma16 on its clockwise side. These mutations did not kill the yeast, because the proteins could still link together into a ring. They were neutral mutations, in other words. But now the ring had to be more complex because it could form successfully only if all three proteins were present and only if they arranged themselves in one pattern.

Thornton and his colleagues have uncovered precisely the kind of evolutionary episode predicted by the zero-force evolutionary law. Over time, life produced more parts—that is, more ring proteins. And then those extra parts began to diverge from one another. The fungi ended up with a more complex structure than their ancestors had. But it did not happen the way Darwin had imagined, with natural selection favoring a series of intermediate forms. Instead the fungal ring degenerated its way into complexity.

FIXING MISTAKES

GRAY HAS FOUND another example of constructive neutral evolution in the way many species edit their genes. When cells need to make a given protein, they transcribe the DNA of its gene into RNA, the single-stranded counterpart of DNA, and then use special enzymes to replace certain RNA building blocks (called nucleotides) with other ones. RNA editing is essential to many species, including us—the unedited RNA molecules produce proteins that do not work. But there is also something decidedly odd about it. Why don't we just have genes with the correct original sequence, making RNA editing unnecessary?

The scenario that Gray proposes for the evolution of RNA editing goes like this: an enzyme mutates so that it can latch onto RNA and change certain nucleotides. This enzyme does not harm the cell, nor does it help it—at least not at first. Doing no harm, it persists. Later a harmful mutation occurs in a gene. Fortunately, the cell already has the RNA-binding enzyme, which can compensate for this mutation by editing the RNA. It shields the cell from the harm of the mutation, allowing the mutation to get passed down to the next generation and spread throughout the population. The evolution of this RNA-editing enzyme and the mutation it fixed was not driven by natural selection, Gray argues. Instead this extra layer of complexity evolved on its own—"neutrally." Then, once it became widespread, there was no way to get rid of it.

David Speijer, a biochemist at the University of Amsterdam, thinks that Gray and his colleagues have done biology a service with the idea of constructive neutral evolution, especially by challenging the notion that all complexity must be adaptive. But Speijer worries they may be pushing their argument too hard in some cases. On one hand, he thinks that the fungus pumps are a good example of constructive neutral evolution. "Everybody in their right mind would totally agree with it," he says. In other cases, such as RNA editing, scientists should not, in his view, dismiss the possibility that natural selection was at work, even if the complexity seems useless.

Gray, McShea and Brandon acknowledge the important role of natural selection in the rise of the complexity that surrounds us, from the biochemistry that builds a feather to the photosynthetic factories inside the leaves of trees. Yet they hope their research will coax other biologists to think beyond natural selection and to see the possibility that random mutation can fuel the evolution of complexity on its own. "We don't dismiss adaptation at all as part of that," Gray says. "We just don't think it explains everything." SA

This article was produced in collaboration with Quanta Magazine, *an editorially independent division of SimonsFoundation.org.*

MORE TO EXPLORE

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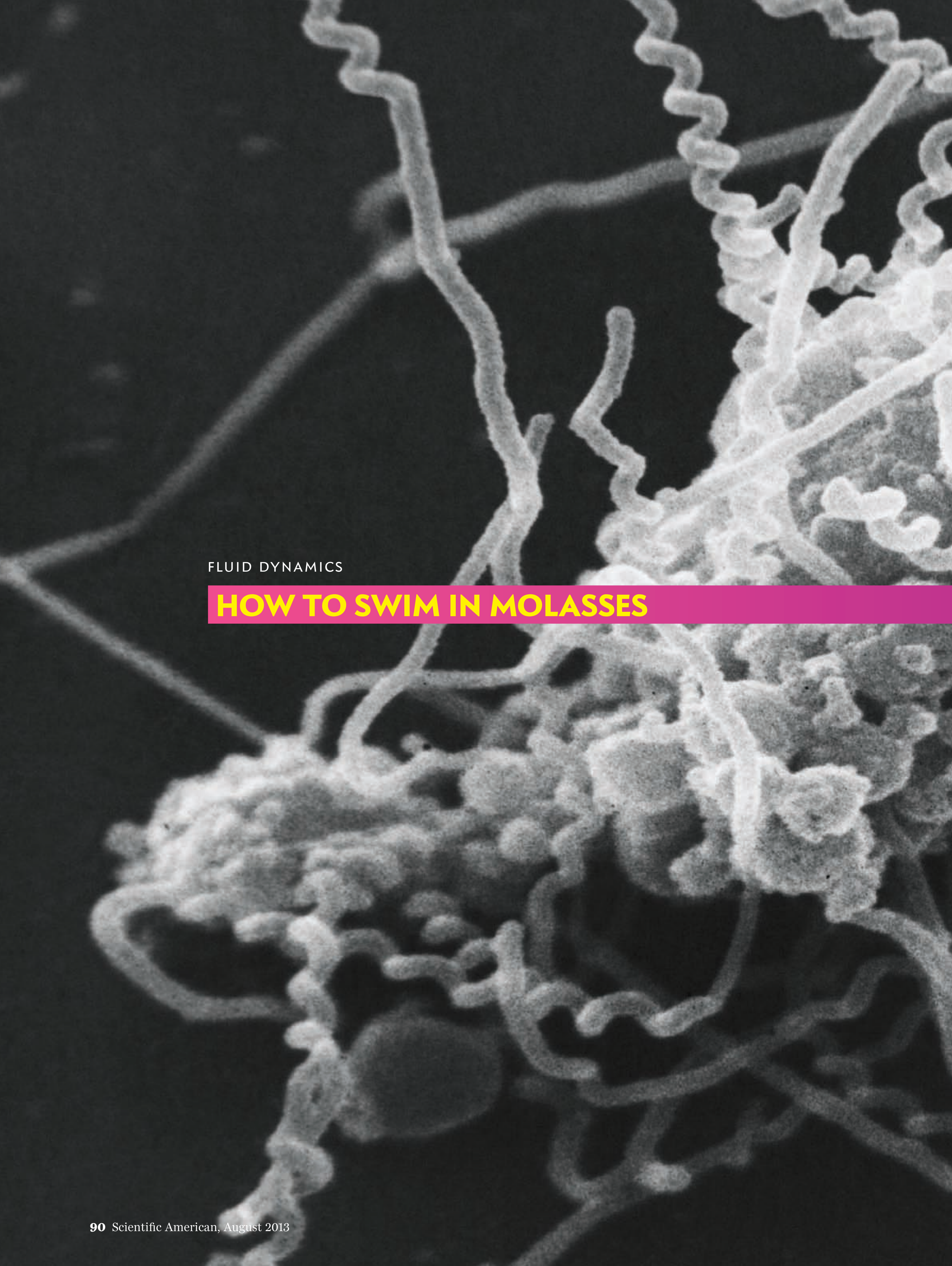
This article and more information about *Quanta Magazine* are available at **www.simonsfoundation.org/quanta**

SCIENTIFIC AMERICAN ONLINE
Read about the role of neutral mutations in disease at **ScientificAmerican.com/aug2013/hidden-mutations**



FLUID DYNAMICS

HOW TO SWIM IN MOLASSES

For some of the world's tiniest and most abundant creatures, moving through water is a fantastically difficult feat

By Ferris Jabr

CORKSCREW-SHAPED bacteria in the genus *Spiroplasma* continuously contort their bodies to swim through the fluids of the plants and insects they infect.

DEVASTATION from the 1919 molasses flood in Boston's North End.

On January 15, 1919, just as Martin Clougherty was waking from a nap, a towering wall of syrup slammed into his bedroom and swept him into the middle of the street. Battered but conscious, he managed to stand in the chest-deep mire flowing past him and wipe great globs of gunk from his eyes. Here and there the splintered remains of his house drifted on a sea of thick, amber fluid. Heaving himself onto a raft of passing debris—his bed frame—he spied a hand just above the muck. He grabbed it and pulled, eventually lifting a gasping woman onto the raft: his sister, Teresa.

Less than 30 yards from the Cloughertys' home, a rickety, five-story-high storage tank of molasses filled to near capacity had split open, releasing more than two million gallons of syrup onto the streets of Boston's North End. A wave 25 feet high and 160 feet wide at its peak demolished buildings, crushed freight cars and tore the Engine 31 firehouse from its foundation. The second floor of the firehouse collapsed onto the first, trapping several firefighters and a stonecutter in a narrow crawl space. The burly men tried to tread molasses as they would water, but every kick required enormous effort. One firefighter drowned from exhaustion. Ultimately the disaster killed 21 people and injured 150 others, many of whom were engulfed by the ooze and could not escape without assistance, as Stephen Puleo describes in detail in his book *Dark Tide* (Beacon Press, 2003).

From a human perspective, a tidal wave of molasses is a freak scenario—something so bizarre that it is difficult to believe at first. For some of the most abundant life-forms on the planet, however, a quagmire of syrup is a moment-to-moment reality. Because they are so tiny, many bacteria, paramecia and other microorganisms spend their lives struggling through water as people would struggle in molasses. In fact, bacteria battle viscous forces millions of times greater than those unleashed on Boston in 1919.

To overcome this predicament, microorganisms have evolved

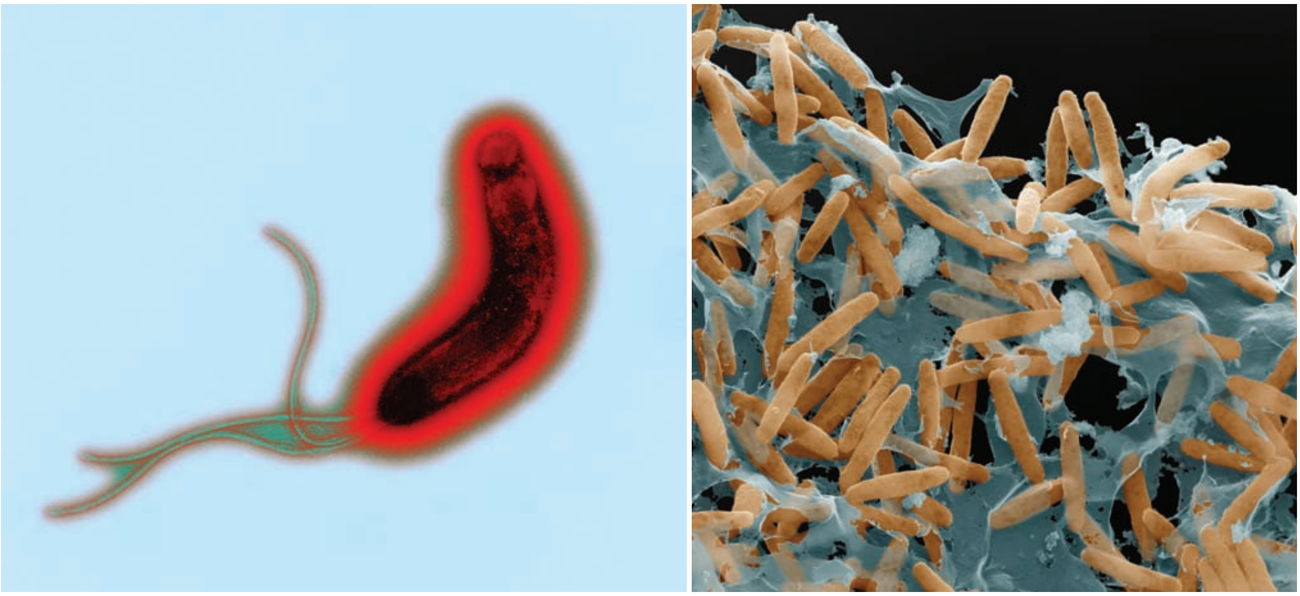
IN BRIEF

In January 1919 a rickety storage tank of molasses split open, releasing an enormous wave of viscous fluid onto the streets of Boston's North End. Many people and animals were engulfed by syrup from which they could not escape without help.

Because they are so tiny, bacteria and other microbes struggle to move through water and various other fluids as we would struggle in molasses. Most microorganisms solve this problem with powerful, whiplike tails or many minuscule hairs that flap like oars.

Some microbes, however, have baffled scientists for years by swimming without obvious external appendages. Recently researchers have begun to solve some of these mysteries, revealing such adaptations as intricate protein motors and slime-thinning enzymes.

PRECEDING PAGES: DAVID M. PHILIPS *Science Source;* COURTESY OF BOSTON PUBLIC LIBRARY *(molasses spill)*



AS IT SWIMS in mucus, *Helicobacter pylori* (*left*) turns a virtually solid gel into a thinner fluid. The soil bacterium *Myxococcus xanthus* (*right*) uses a protein motor to glide along surfaces without external appendages; a similarly limbless ocean bacterium may do the same.

sophisticated and wacky ways of moving all their own. Bacteria and other kinds of Lilliputian life do not simply swim—they push and pull, twitch and skitter, spin and corkscrew their way through fluids and across slimy surfaces. Most microbes depend on obvious appendages to get around, but certain minuscule critters have baffled scientists for decades by refusing to reveal their tricks. In recent years, with the help of increasingly powerful cameras and microscopes, biologists have solved some of these long-standing mysteries and uncovered an array of previously unknown adaptations. It turns out that even some closely studied microbial species travel in ways scientists never noticed before. New research has unveiled intricate protein motors concealed within bacterial cells, slime-thinning enzymes that modify a microorganism's environment as it swims to make the journey easier and a bacterium that uses miniature grappling hooks to slingshot itself through fluid.

"If the world were suddenly covered in molasses today, people would have real problems," says Jacinta Conrad, who studies bacteria and complex fluids at the University of Houston. "But bacteria reproduce quite quickly, and they are quite adaptable, which are some things that have given them the ability to conquer the world. If they don't have the right appendages or tools to move through fluids, there's a good chance some of their progeny will have them in the near future."

Lilliputian forms of life do not simply swim—they push and pull, twitch and skitter, spin and corkscrew their way through fluids and across slimy surfaces.

A STICKY SITUATION

BACTERIA IMMERSED IN WATER and people submerged in molasses are in more or less the same sticky situation. One can predict how easily a bacterium, person or any other living thing will move through a given fluid by calculating the relevant Reynolds number, which, in this case, takes into account the viscosity and density of the fluid and the velocity and size of the organism. The higher the Reynolds number, the more likely everything will go along swimmingly.

In most situations, human swimmers enjoy very high Reynolds numbers. The Reynolds number for an adult man in water, for example, is around one million. In contrast, many microscopic swimmers permanently inhabit a low-Reynolds-number world, as American physicist Edward Mills Purcell explained in his famous 1974 lecture "Life at Low Reynolds Number." Some bacteria must combat Reynolds numbers of around 10^{-5}. To illustrate this fact, Purcell compared a microbial swimmer to a person submerged in a swimming pool full of molasses. In such circumstances, the Reynolds number for an adult man plummets to around 130.

To make matters worse, a man immersed in molasses would not get anywhere with the kinds of symmetric swimming strokes that would propel him in water. Each repetitive stroke would only undo what was done before. Pulling his arm toward himself would move molasses away from his head, but reaching up to repeat the stroke would push the molasses back where it was before. He would stay in place, like a gnat trapped in tree sap. Likewise, bacteria and other microbes cannot use reciprocal movements to travel through any fluid, be it water in the ocean or a pond or the nutritious broth sloshing through the human gut. So they have evolved entirely different ways of swimming.

Microorganisms' two most common solutions to the problems posed by low Reynolds numbers are cilia and flagella. Short, hairlike projections called cilia coat the surfaces of paramecia and other single-celled protozoans, which are distinct from bacteria. To move, paramecia constantly row their cilia like miniature oars, albeit in an unusual way. During the power stroke, the cilia are fully extended, creating a lot of drag; during the recovery stroke, however, the cilia flex and curl into little question marks, creating much less drag. Because of this difference in drag, the power stroke pushes the microorganisms forward more than the recovery stroke pulls them back—so they swim.

Many species of bacteria, such as the extensively studied *Escherichia coli,* propel themselves with helical, whiplike filaments of protein called flagella. Flagella look like long cilia but behave quite differently. Instead of rowing, a bacterial flagellum rotates, pushing the cell to which it is attached through a fluid somewhat like a corkscrew boring into a cork. When the flagellum turns counterclockwise, the bacterium moves forward in a straight line; quickly switching to clockwise rotation allows a microbe to tumble and change directions.

In a low-Reynolds-number world, inertia is practically meaningless. Whereas a human swimmer could take a few backstrokes, stop and still glide along for a while, some microorganisms must move ceaselessly through fluids if they are to get anywhere at all. If a bacterium stopped spinning its flagella, it would reach a complete standstill in a distance less than one tenth of the diameter of a hydrogen atom, according to calculations by Howard Berg of Harvard University, a pioneer of research on bacterial movement.

MICROBIAL MYSTERIES

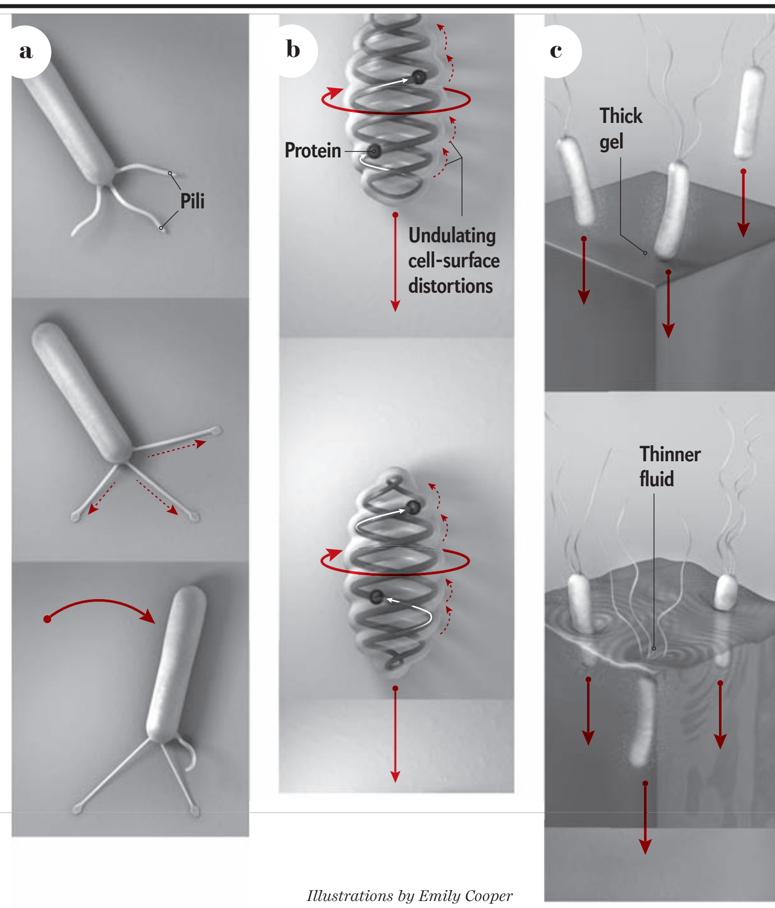
SINCE THE 1970s biologists have learned much about microbes that rely on cilia and flagella. Other microbes, however, were not so easy to figure out: they moved without using cilia, flagella or any other obvious means of propulsion. In the past 10 years scientists have finally started to solve some of these mysteries of microbial locomotion, often with the help of keen imaging tools not previously available. "The past few decades have yielded one surprising finding after another of different ways bacteria have for getting around," says Mark McBride, who studies bacteria at the University of Wisconsin–Milwaukee. "Some of the most surprising discoveries are very abundant bacteria that swim but don't have any flagella."

Fusilli-shaped bacteria in the genus *Spiroplasma,* for example, swim through the juices of the plants and insects they infect, although they have no swimming appendages of any kind. Joshua W. Shaevitz, now at Princeton University, and his colleagues think that *Spiroplasma* bacteria have evolved a rather kinky way of moving. Helical ribbons of protein inside the bacteria provide structural support. In 2005 Shaevitz and his colleagues took a close look at these ribbons with a sophisticated microscopy technique that splits and refocuses polarized light to enhance the contrast and detail of the image. Their observations revealed that tiny protein motors twist one segment of the ribbons in one direction and another segment in the opposite direction, creat-

BEYOND CILIA AND FLAGELLA

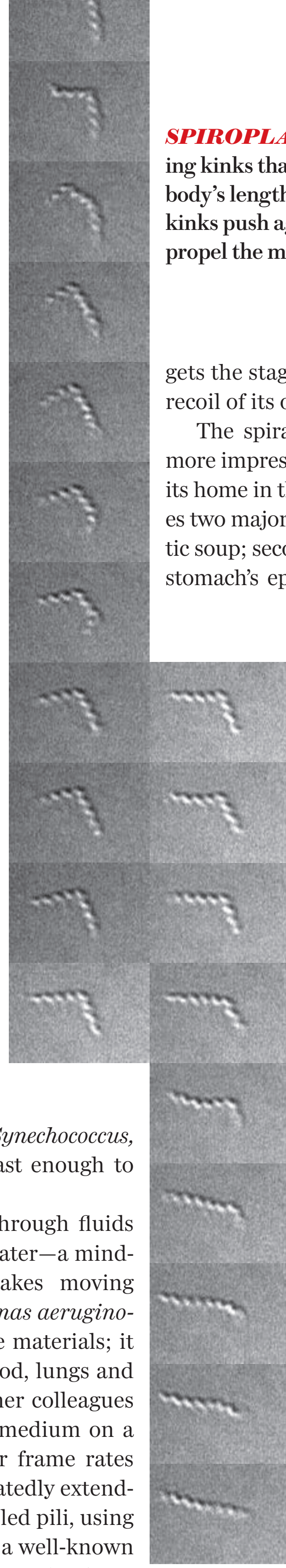
Three Wacky Ways That Microbes Move

Most microbes swim with obvious appendages, such as flapping hairs known as cilia and longer spinning or undulating filaments called flagella. Other microorganisms move in much more surprising ways. To move through fluid covering a solid surface, *Pseudomonas aeruginosa* **a** first anchors itself to the surface with several taut and sticky protein threads called pili. Then, it suddenly detaches a single pilus, sending its body skittering. Pill-shaped ocean bacteria in the genus *Synechococcus* **b** likely rely on intricate internal motors in which round proteins race along helical tracks, rippling the cell surface and whirling the whole microbe forward. Collectively, groups of *H. pylori* **c**, a bacterium that has evolved to colonize the human stomach, catalyze a chemical reaction that both neutralizes hydrochloric acid and transforms the stomach's mucus layer from a thick gel into a thinner fluid.



Illustrations by Emily Cooper

ing a 111-degree kink where the two segments meet—similar to the way a phone cord tangles. These kinks rapidly and continuously travel from one end of the cell to another in waves, forming crooks in the cell body itself that push against surrounding fluids to move the bacterium forward.



SPIROPLASMA **bacteria swim by forming kinks that travel in waves along the cell body's length (*top to bottom in strips*). The kinks push against surrounding fluid to propel the microbes forward.**

COURTESY OF JOSHUA W. SHAEVITZ *Princeton University*

Synechococcus, a group of pill-shaped photosynthetic ocean bacteria, continues to flummox scientists. Like *Spiroplasma,* the *Synechococcus* bacterium manages to swim even though it lacks an evident means of moving. In a 2012 paper George Oster of the University of California, Berkeley, and Kurt Ehlers of the Desert Research Institute–Reno in Nevada proposed the most plausible explanation to date. The pair found insight in recent research on an unrelated soil bacterium called *Myxococcus xanthus.* Scientists knew that *M. xanthus* sometimes glides along surfaces without using any external appendages, but they were not sure how.

In 2011 Oster's Berkeley colleagues David Zusman and Beiyan Nan tagged proteins known to help *M. xanthus* move with fluorescent molecules that glow cherry red in ultraviolet light. With a powerful microscope, they observed blushing proteins of different sizes running along a loop of twisted protein fibers, creating lumps in the cell surface that essentially act like tank treads. Ehlers and Oster think *Synechococcus* relies on a similar system—but one that operates in a much higher gear. According to their mathematical model, if an analogous protein motor exists inside *Synechococcus,* "nothing in physics prevents" it from spinning fast enough to move the bacterium through water, Oster says.

Some bacteria have evolved ways to travel through fluids and gels thousands of times more viscous than water—a mind-boggling feat, considering that their size makes moving through water alone a huge challenge. *Pseudomonas aeruginosa* lives in soil, in water and on many man-made materials; it also thrives in the human body, infecting the blood, lungs and urinary tract in particular. In 2011 Conrad and her colleagues filmed *P. aeruginosa* moving through a viscous medium on a piece of glass, using cameras with much higher frame rates than those in earlier studies. The bacterium repeatedly extended and reabsorbed sticky, hairlike appendages called pili, using them like grappling hooks to pull itself forward—a well-known microbial move. The new film footage revealed a surprise, however: *P. aeruginosa* sometimes detached a single pilus while keeping others taut, slingshotting itself across the glass 20 times faster than usual.

Conrad and her colleagues think that the bacterium's super-speedy skittering reduces the viscosity of the surrounding fluid through a process known as shear thinning. Non-Newtonian fluids, such as molasses, ketchup and the kind of slime *P. aeruginosa* often moves through, become less viscous when under pressure. Just as giving a Mrs. Butterworth's bottle a squeeze gets the stagnant syrup it holds flowing, *P. aeruginosa* uses the recoil of its own body to thin out the sticky fluid around it.

The spiral-shaped *Helicobacter pylori* has evolved an even more impressive way to reduce viscosity. A bacterium that makes its home in the human stomach, the ulcer-inducing *H. pylori* faces two major challenges: first, it must survive the stomach's caustic soup; second, it must cross a thick layer of mucus to reach the stomach's epithelial cells, its preferred niche. To solve the first problem, *H. pylori* secretes the enzyme urease, which catalyzes a chemical reaction that turns urea in the stomach into ammonia and carbon dioxide, neutralizing hydrochloric acid. Biologists have always assumed that *H. pylori* relies on the power of its spinning flagella to bore its way through mucus. Yet when Jonathan Celli, now at the University of Massachusetts Boston, and his colleagues deprived *H. pylori* of urea in the laboratory in 2009, it could not move through imitation mucus. The same chemical reaction that neutralizes acid in the stomach, Celli's research suggests, also changes the conformation of proteins in mucus, transforming it from a virtually solid gel into a more navigable fluid.

All around us—and inside us—infinitesimal creatures such as *H. pylori* reckon with daunting physical forces to which we are oblivious. A casual look at bacteria under the microscope, twirling like runaway carousels or zigzagging with apparent ease, does not reveal their struggle. To understand what it would be like to live and move as a microbe, we must immerse ourselves in a bizarre alternative reality—in a world where water is as thick as molasses. What Martin Clougherty experienced in 1919 is what many microorganisms endure every second of their brief, brutal lives. For a microbe, flapping a cilium or jitterbugging to move a fraction of a millimeter is not a trivial act—it is a monumental feat and a testament to eons of evolutionary grit. SA

***Ferris Jabr** is an associate editor at* Scientific American.

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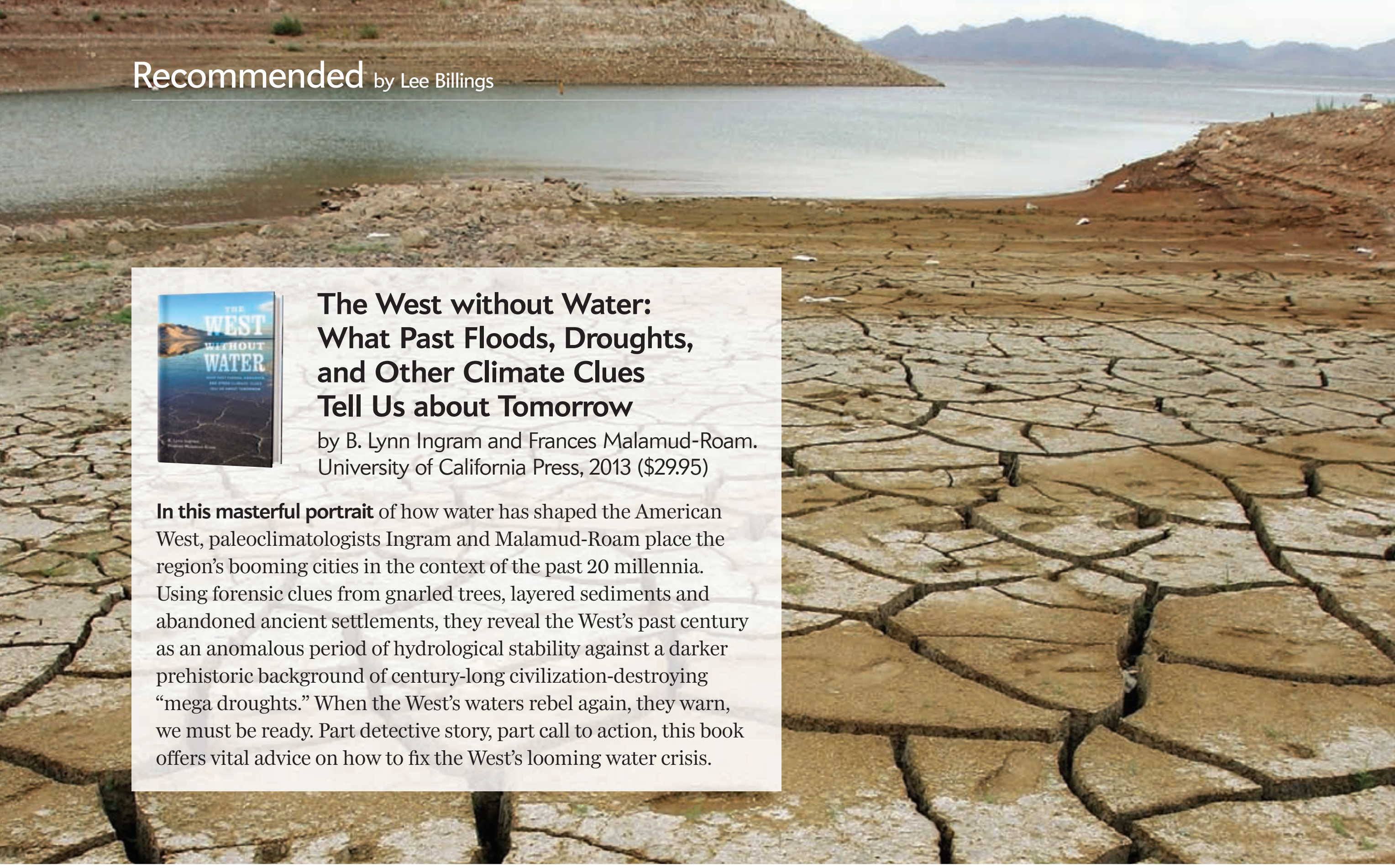
To read more about the physics of the Great Molasses Flood, visit ScientificAmerican.com/aug2013/molasses-flood-physics



Recommended by Lee Billings

The West without Water: What Past Floods, Droughts, and Other Climate Clues Tell Us about Tomorrow

by B. Lynn Ingram and Frances Malamud-Roam. University of California Press, 2013 ($29.95)

In this masterful portrait of how water has shaped the American West, paleoclimatologists Ingram and Malamud-Roam place the region's booming cities in the context of the past 20 millennia. Using forensic clues from gnarled trees, layered sediments and abandoned ancient settlements, they reveal the West's past century as an anomalous period of hydrological stability against a darker prehistoric background of century-long civilization-destroying "mega droughts." When the West's waters rebel again, they warn, we must be ready. Part detective story, part call to action, this book offers vital advice on how to fix the West's looming water crisis.

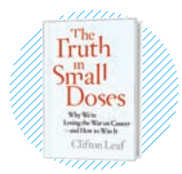
ETHAN MILLER *Getty Images*

Betting on Famine: Why the World Still Goes Hungry

by Jean Ziegler. New Press, 2013 ($26.95)

Nearly one billion people throughout the world suffer from hunger and malnutrition. This shameful statistic stems not from a failure of agriculture, technology or science but from inhumane and shortsighted politics, contends Ziegler, a former special rapporteur for the United Nations. In grim detail, he explains hunger's high human and economic costs. He also investigates hunger's modern, geopolitical causes, drawing from recent examples such as the sanctions against Iraq during Saddam Hussein's rule, in which the international community withheld food and medicine on the grounds that the supplies could be used by Iraq's military. As a result, several hundred thousand Iraqi children needlessly starved to death. Preventing hunger is possible, Ziegler argues, if the world recognizes that access to food is a basic human right. *—Marissa Fessenden*

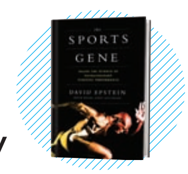
The Truth in Small Doses: Why We're Losing the War on Cancer—and How to Win It



by Clifton Leaf. Simon & Schuster, 2013 ($27)

The U.S. Congress declared a "war on cancer" with the 1971 National Cancer Act and poured money into fighting the disease. Yet ever since, new cancer cases have risen three times faster than the U.S. population. According to Leaf, a journalist and cancer survivor, the act failed because of the flawed research culture it spawned. In this history of the fight against cancer, he describes how scientists often cannot secure funding for risky research in a culture that rewards competition over collaboration. The final section is a call to shift funding from narrow projects to broadly skilled researchers and urges patients to become better advocates for progressive change. Without such steps, Leaf says, the war on cancer has no chance of being won. *—Marissa Fessenden*

The Sports Gene: Inside the Science of Extraordinary Athletic Performance



by David Epstein. Current, 2013 ($26.95)

Ever since the successful mapping of the human genome a decade ago, scientists have sought genes that distinguish top athletes from the rest of us, yielding fresh insights into the age-old question of nature versus nurture. As a former competitive runner and current *Sports Illustrated* senior writer, Epstein is well equipped to explain the complexities of the "sports gene" search. Time and time again, his deeply researched and nuanced investigations of the genetics underlying the athleticism of different races, genders and individuals reinforce a comforting, commonsense conclusion: excelling at sports isn't just a matter of natural talent or nurtured practice—it's both.

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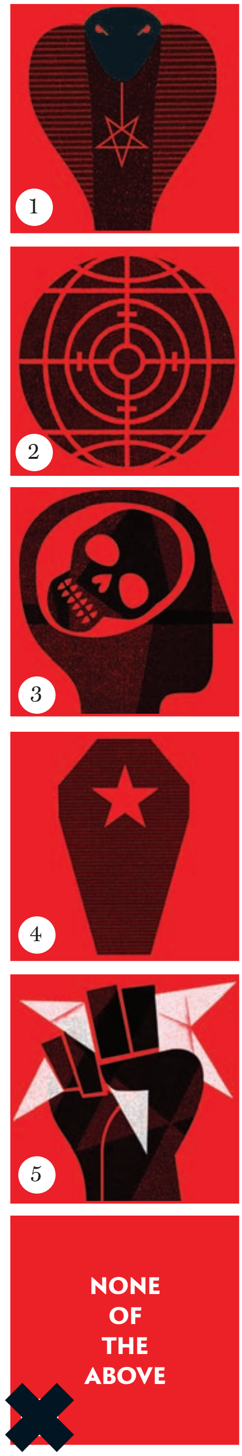
Viewing the world with a rational eye

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His book *The Believing Brain* is now out in paperback. Follow him on Twitter @michaelshermer

Five Myths of Terrorism

Why terror doesn't work



Because terrorism educes such strong emotions, it has led to at least five myths. The first began in September 2001, when President George W. Bush announced that "we will rid the world of the evildoers" and that they hate us for our "our freedoms." This sentiment embodies what Florida State University psychologist Roy F. Baumeister calls "the myth of pure evil," which holds that perpetrators commit pointless violence for no rational reason.

This idea is busted through the scientific study of aggression, of which psychologists have identified four types that are employed toward a purposeful end (from the perpetrators' perspective): *instrumental violence,* such as plunder, conquest and the elimination of rivals; *revenge,* such as vendettas against adversaries or self-help justice; *dominance and recognition,* such as competition for status and women, particularly among young males; and *ideology,* such as religious beliefs or utopian creeds. Terrorists are motivated by a mixture of all four.

In a study of 52 cases of Islamist extremists who have targeted the U.S. for terrorism, for example, Ohio State University political scientist John Mueller concluded that their motives are often instrumental and revenge-oriented, a "boiling outrage at U.S. foreign policy—the wars in Iraq and Afghanistan, in particular, and the country's support for Israel in the Palestinian conflict." Ideology in the form of religion "was a part of the consideration for most," Mueller suggests, "but not because they wished to spread Sharia law or to establish caliphates (few of the culprits would be able to spell either word). Rather they wanted to protect their co-religionists against what was commonly seen to be a concentrated war on them in the Middle East by the U.S. government."

As for dominance and recognition, University of Michigan anthropologist Scott Atran has demonstrated that suicide bombers (and their families) are showered with status and honor in this life and the promise of women in the next and that most "belong to loose, homegrown networks of family and friends who die not just for a cause but for each other." Most terrorists are in their late teens or early 20s and "are especially prone to movements that promise a meaningful cause, camaraderie, adventure and glory," he adds.

Busting a second fallacy—that terrorists are part of a vast global network of top-down centrally controlled conspiracies against the West—Atran shows that it is "a decentralized, self-organizing and constantly evolving complex of social networks." A third flawed notion is that terrorists are diabolical geniuses, as when the 9/11 Commission report described them as "sophisticated, patient, disciplined, and lethal." But according to Johns Hopkins University political scientist Max Abrahms, after the decapitation of the leadership of the top extremist organizations, "terrorists targeting the American homeland have been neither sophisticated nor masterminds, but incompetent fools."

Examples abound: the 2001 airplane shoe bomber Richard Reid was unable to ignite the fuse because it was wet from rain; the 2009 underwear bomber Umar Farouk Abdulmutallab succeeded only in torching his junk; the 2010 Times Square bomber Faisal Shahzad managed merely to burn the inside of his Nissan Pathfinder; and the 2012 model airplane bomber Rezwan Ferdaus purchased faux C-4 explosives from FBI agents. Most recently, the 2013 Boston Marathon bombers appear to have been equipped with only one gun and had no exit strategy beyond hijacking a car low on gas that Dzhokhar Tsarnaev used to run over his brother, Tamerlan, followed by a failed suicide attempt inside a land-based boat.

A fourth fiction is that terrorism is deadly. Compared with the annual average of 13,700 homicides, however, deaths from terrorism are statistically invisible, with a total of 33 in the U.S. since 9/11.

Finally, a fifth figment about terrorism is that it works. In an analysis of 457 terrorist campaigns since 1968, George Mason University political scientist Audrey Cronin found that not one extremist group conquered a state and that a full 94 percent failed to gain even one of their strategic goals. Her 2009 book is entitled *How Terrorism Ends* (Princeton University Press). It ends swiftly (groups survive eight years on average) and badly (the death of its leaders).

We must be vigilant always, of course, but these myths point to the inexorable conclusion that terrorism is nothing like what its perpetrators wish it were. SA

SCIENTIFIC AMERICAN ONLINE
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Illustration by Matthew Hollister

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 34 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Embrace the Ick

Medicine is art, science and gag suppression

The long-running TV series *M*A*S*H* featured tireless and dedicated surgeons. *ER,* another long-lived series, featured heroic and complicated emergency health care workers. The recently concluded sitcom *30 Rock* featured Dr. Leo Spaceman.

Usually pronounced "spah-CHEH-mun" (but occasionally astronautically), Spaceman somehow practices everything from psychiatry to transplant surgery to ophthalmology to obstetrics—when a new father asks Spaceman why the just delivered baby is "covered with goop," the doctor replies, "Because everything about this is disgusting."

Childbirth is especially messy. But think about medicine long enough, and you'll eventually agree with Everydoc Spaceman that it's all disgusting. Which brings us to fecal transplants. Of course.

Officially called a fecal microbiota transplantation, or FMT, the procedure involves the insertion of a small, diluted sample of stool from a donor into the colon of a recipient. (Clearly disgusting.) The swap imports a healthy community of bacteria, the intestinal microbiota, into the system of someone lacking healthful intestinal flora. (Billions on billions of microscopic organisms swimming around inside your guts.) Numerous studies have found the fecal transplant's bacterial army to be highly effective fighters against *Clostridium difficile* colitis, which causes terrible cramps and frequent bloody diarrhea. (Getting queasy.) The usual antibiotic treatment can disrupt the healthful diversity of gut bacteria. (Microbial mass murder.) And it is often unsuccessful. Researchers publishing in the *Journal of Clinical Gastroenterology* thus have suggested that the treatment should be considered as a first choice rather than a last resort. (Reading medical journals, blech.)

Unfortunately, the Food and Drug Administration recently made it harder to send in the microbial cavalry. In May the agency decided to require doctors to file an Investigational New Drug application before performing the procedure. As Judy Stone (M.D.) points out in her *Scientific American* blog Molecules to Medicine, the extra time and expense associated with the rule curtail the use of FMT. Stone specifically cites what she calls the "'ick' factor" as a barrier to more widespread acceptance of this treatment: "Thus far, resistance to transplants I have recommended has not come from patients or their families, who are desperate for relief. It has come from other health care workers, especially physicians, who seem to find the idea particularly distasteful." Because a fecal transplant is gross, but cramps and bloody diarrhea are aesthetically pleasing?

With the intent of eradicating the fecal transplant ick factor, I reiterate that "everything about this is disgusting."

In *The African Queen,* Oscar winner Humphrey Bogart could afford to be skeeved out by leeches all over him because surgeons weren't attempting to reattach a finger. In real life, leeches are routinely used at trauma centers and for microsurgical procedures to keep blood flowing, thanks to their production of natural anticoagulants.

Maggots are often used to dine on the dead flesh around various wounds because they're better at cleaning up the area than doctors are. "Maggot therapy" sounds bad, of course, so the term "larval therapy" was suggested. Finally, "biosurgery" got maggots out of the name, but they're still in the wounds.

Note to FMT proponents: for marketing purposes, you really have to downplay any reference to feces. It's no accident nuclear magnetic resonance (NMR) applied to radiological picture making became magnetic resonance imaging (MRI). Voilà, no nukes.

Leeches and maggots easily make my disgusting case. In more pedestrian examples, we have toenail fungus, bunions, hammertoe and foot funk. Dermatology is a constant stream of skin eruptions, warts and moles. Dentistry is hands in strangers' mouths. Orthopedics is cracking bones and pushing them around. Ear-nose-throat is wax-snot-phlegm. Brain surgery, transplant surgery, urology, proctology, gynecology, all nasty. Even the lollipop the pediatrician gives your kid is gonna wind up oozing a slimy trail of sugary saliva and hand schmutz down your car's dashboard on the drive home.

Attend one parasitology lecture, even glance at just one photo of a guinea worm, and you'll beg for something clean and simple like a friend's stool. So embrace the Microbiome Transplant™ with a smile. It belongs. Because everything about this is disgusting. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/aug2013

Illustration by Matt Collins

August 1963

Supersonic Dreams

"Stimulated by a 20-month-old British-French plan to build a supersonic commercial jet transport, the Administration has asked Congress to authorize up to $750 million for the development of such an aircraft by U.S. manufacturers. It is felt that the cost of development, estimated at $1 billion, would be too great for private industry. This would be the first time the Government has provided a direct subsidy for the development of a commercial airplane. Najeeb E. Halaby, head of the Federal Aviation Agency, envisions a transport in operation before 1971. Halaby believes it will be possible to produce a craft that is faster than the British-French Concorde and to introduce it at about the same time."

August 1913

From Rivalry to War

"In a recent number of *La Nature,* there appears a critical estimate of the relative air strength of Germany and France. Inasmuch as these two powers have been keen rivals in attaining what may be called a supremacy of the air, an abstract of our French contemporary's article will doubtless prove of interest to our readers. If the actual status of this aerial fleet is secret, that of plans and projects is doubly so. French inferiority is obvious, and also French efforts to diminish that inferiority."

See a photo album on the art of war in 1913 at ***www.ScientificAmerican.com/jul2013/warfare***

Tsetse Fly

"The Sesse Islands in Lake Victoria are a specimen of Nature's jewelry. But, exquisite as is their scenery, the Sesses form a charnel house. Death is over them. This is a land of silence. The voice of the child is unheard, the chant of Baganda women, so full of cadence, comes no more over the waters. The bark hut villages that for centuries sheltered the finest types of the African race, in mind and body, are rotting ruins. Why this desolation of all that is human? Because of a sleeping death. What causes the sleep that kills? A fly that breeds the tiniest murderer known to the world."

August 1863

American Art Abroad

"The London *Times* says: 'The reputation of Mr. [Frederic] Church, the most eminent American landscape painter, has been brought to this country by his 'Niagara,' and 'Heart of the Andes.' His 'Icebergs off the Coast of Labrador,' now exhibited at the German Gallery, affords an excellent opportunity to form a conception of what landscape painting in the United States is aiming at and achieving. The picture altogether is a noble example of the application of the landscape painter's art to the rendering of grand, beautiful, and unfamiliar aspects of nature, only accessible at great cost of fatigue and exposure, and even at peril of life and limb.'"

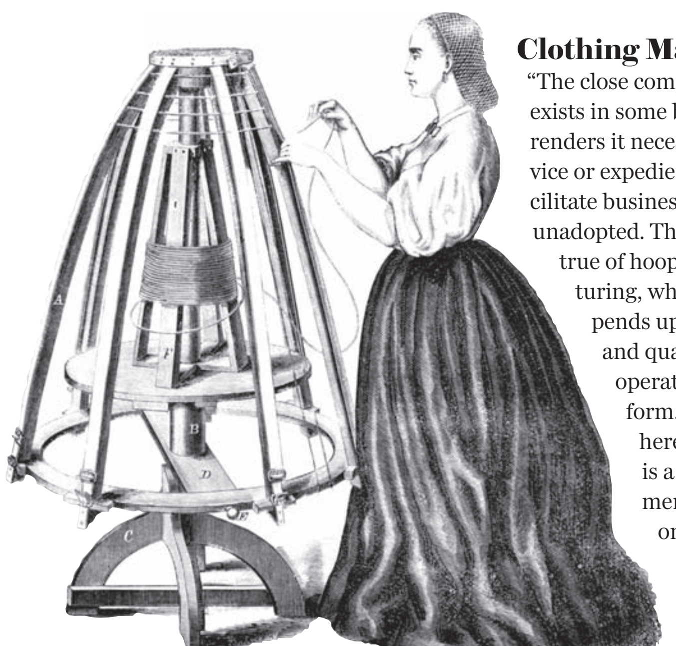
The Sun

"If the sun were composed of coal, it would last at the present rate only 5,000 years. The sun, in all probability, is not a burning but an incandescent body. Its light is rather that of a glowing molten metal than that of a burning furnace. But it is impossible that the sun should constantly be giving out heat, without either losing heat or being supplied with new fuel. Assuming that the heat of the sun has been kept up by meteoric bodies falling into it, and proof has been given of such fall, it is possible from the mass of the solar system to determine approximately the period during which the sun has shone as a luminary. The limits lie between 100 millions and 400 millions of years."

Clothing Machine

"The close competition which exists in some branches of trade renders it necessary that no device or expedient which will facilitate business should be left unadopted. This is particularly true of hoop skirt manufacturing, where so much depends upon the amount and quality of work an operator is able to perform. The skirt frame herewith illustrated is a great improvement upon the old ones in general use."

For a look at agricultural machines from the same period, see ***www.ScientificAmerican.com/aug2013/agriculture-1863***



MODERN DRESSMAKER, back when clothing was mostly made by hand, 1863

SCIENTIFIC AMERICAN, VOL. IX, NO. 5; AUGUST 1, 1863

Living in Harm's Way

Damage from storms will rise sharply, even without climate change

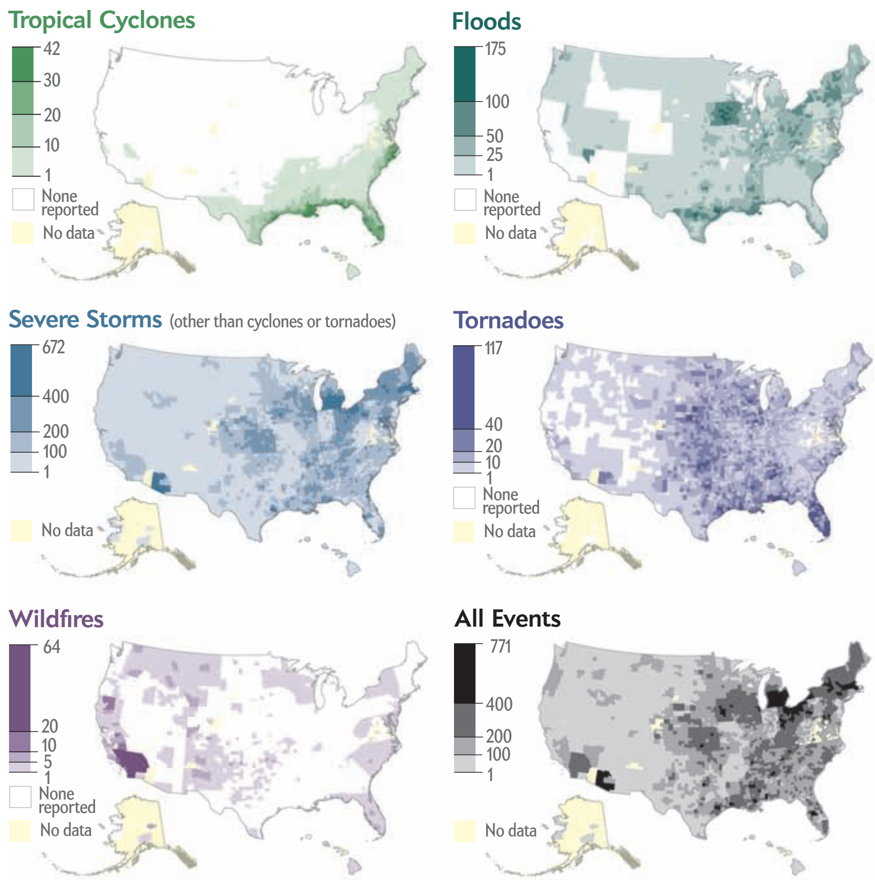
Extreme weather could cause four times as much economic loss in the U.S. by 2050 as it does today—without any increase in the frequency or intensity of hurricanes, tornadoes or lightning. That is because the population will be larger and richer and because more Americans are moving to the Eastern seaboard, the Gulf Coast and other storm-ridden places.

The frequency of natural hazards varies across the country (*top map*), but nationwide, average annual losses from all of them over the past 50 years amounted to $10 billion to $13 billion (not including business disruption). By 2050 the price tag will double in many counties, and in some it will swell by four or six times or more (*bottom map*), according to Benjamin L. Preston, deputy director of the Climate Change Science Institute at Oak Ridge National Laboratory. The highest increases will be driven mostly by rising population. If society is concerned about future risk, Preston says, it has to pay closer attention to where people are migrating. —*Mark Fischetti*

SCIENTIFIC AMERICAN ONLINE
To see where population has grown most, go to ScientificAmerican.com/aug2013/graphic-science

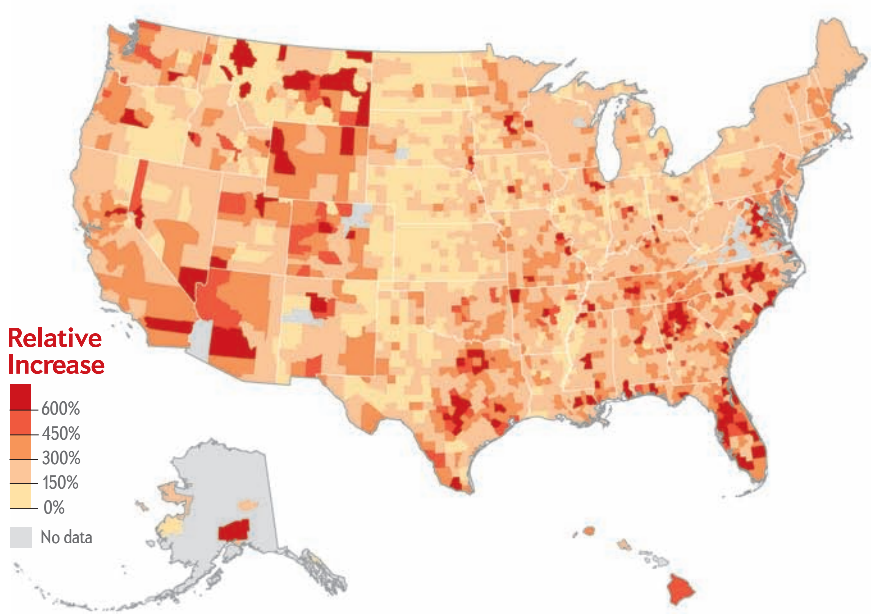
Severe Weather (number of events causing loss, by county, 1960–2008)

Different natural hazards peak in various regions of the U.S., but they add up most in the Northeast



Potential Rise in Economic Losses (2009–2050, relative to actual 1960–2008 losses)

Counties where population and personal income rise significantly could incur much higher disaster bills



SOURCE: "LOCAL PATH DEPENDENCE OF U.S. SOCIOECONOMIC EXPOSURE TO CLIMATE EXTREMES AND THE VULNERABILITY COMMITMENT," BY BENJAMIN L. PRESTON, IN *GLOBAL ENVIRONMENTAL CHANGE*, VOL. 23, NO. 4; AUGUST 2013

Maps by XNR Productions

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Science and Education

Transforming Learning and Discovery

It has always been the case, and will remain so, that students want to get the best results and teachers want to find the best ways to help them. But today the ways in which they learn and teach have changed seismically. From interactive textbooks and tests to adaptive learning, “flipped classrooms”, and customized and open source content, there has never been such an exciting time to be part of the education landscape. That’s because to complement traditional approaches, there are now so many new tools available — providing more interactivity, greater relevance and, ultimately, better results.

Macmillan Science and Education is proud of the important part we play at all stages of the learning journey. We are a place for curious minds who are working to develop the next generation of ideas. We are home to teachers, researchers, entrepreneurs and technologists — leaders in the fields of science and education who share a passion for transforming lives.

We operate in 120 countries around the world and have a deep understanding of what teachers and students want and need. With their challenges in mind, we are privileged to work with leading authors who provide the high-quality content that, when combined with our expertise in digital delivery, data and analytics, helps teachers and students access the right mix of learning materials and methods to achieve their educational goals.

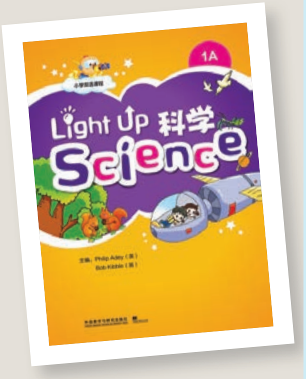
FOR OVER 170 YEARS, MACMILLAN HAS STIMULATED THINKING IN SCIENCE, EDUCATION AND IN LIFE. WE CHAMPION IDEAS FROM AROUND THE WORLD TO SUPPORT PEOPLE THROUGH THEIR DEVELOPMENT.

Progress in education and science are interlinked. Discovery fuels learning, and research is where it all starts. The dissemination of new thoughts and ideas, along with challenges to current and past thinking all stimulate progress. Innovation shows no signs of slowing. We have a vision to push the frontiers of learning and discovery by providing the best content and the most innovative technology-enabled solutions. That’s because the discoveries of today influence what subjects our children will study, how businesses will operate, how social policy will be shaped and even how we will see and understand ourselves.

ANNETTE THOMAS, CEO,
MACMILLAN SCIENCE AND EDUCATION

macmillan
Science and Education

Transforming Learning and Discovery



A NEW WAY OF LEARNING IN CHINA

Light Up Science is a new bilingual science learning course in Chinese and English for schoolchildren in China. Science education is a key focus for schools in China, ensuring that students have both the right scientific and English-language skills to meet the growing demand for scientific researchers. *Light Up Science* models a pioneering approach to primary science learning. Students are encouraged to become active explorers of the natural world, progressing from innate inquisitiveness to more structured and rigorous investigation and experiment. The multi component course is composed of a mix of workbooks and digital content and rich multimedia teaching resources to support classroom learning.

Charlotte Liu, Managing Director, Macmillan Science (Greater China) and Education (Asia)

MACMILLAN AUTHORS AT THE FOREFRONT OF CHANGE IN THE CLASSROOM

Besides driving the "flipped classroom" model, digital resources are also critical tools for what happens in the classroom. From student polling to interactive visualization, digital tools have opened up new ways for instructors to engage their students. Overall, this enables instructors to take a multimodal approach, thereby creating a more dynamic and inclusive learning environment.

Robert Lue, *Biology: How Life Works*

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Simon Walsh, Managing Director at *Maths Doctor*, ex-maths teacher and start-up entrepreneur

I put on the headset, and I can hear my tutor on the other end. I use an interactive whiteboard and pen to write my answers and questions. All my lessons are much better because I get undivided attention and I don't have to rush to keep up with everyone else.

Isobel, aged 12

INTERACTIVE HOMEWORK IMPROVES GRADES

Sapling Learning provides interactive homework and instruction, proved to improve student learning outcomes. Experience has shown that the more students do outside the classroom, the more they succeed in class and beyond.

Jamie Caras, Ph.D., President and CEO, *Sapling Learning*

Using *Sapling Learning* directly correlates to improved learning outcomes. The more students use it, the more successful they are.

Laurie Parker, Purdue Associate Professor, who uses *Sapling Learning* with her organic chemistry students

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W. H. FREEMAN

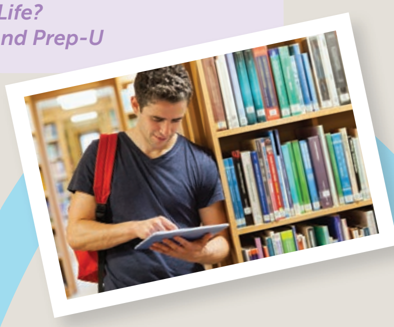
A text developed and produced by a well-qualified team – including a content expert as well as experts in educational research and assessment design – can serve several important goals beyond content delivery. This is why content that has been extensively reviewed and edited for clarity, accuracy, and a consistent voice is an extremely valuable part of an effective college course.

Jay Phelan, *What Is Life? A Guide to Biology and Prep-U*

A LIFELONG JOURNEY

Helping the born curious to stay curious

EVER CURIOUS



POST-GRADUATE

Helping academic researchers to succeed

DIGITAL PUBLISHING KEEPS PACE WITH LANGUAGE EVOLUTION

Language change isn't something new or alarming: it is the norm. It's the job of dictionaries to keep pace with new words and new meanings. Digital publishing means we can respond to these changes more rapidly than was possible in the days of print, when a new usage might wait five years to get into a revised edition. Digital media are democratizing the process, too. People used to refer to the dictionary as if it were a higher authority. But through social media, blogs, and wiki-style sites, users can add their own entries and participate in the debate about the way language is developing, allowing a greater sense of ownership and community.

Michael Rundell, Editor-in-Chief, Macmillan Dictionary and Stephen Bullon, Publisher, Macmillan Dictionaries

MACMILLAN DICTIONARY

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John Carroll, Publishing Director, Nature Education

After teaching freshman college biology for 25 years, I think it is great that my students now get an e-textbook with immediate access to great articles and interactive science examples.

Biology Professor, Rocky Mountain College