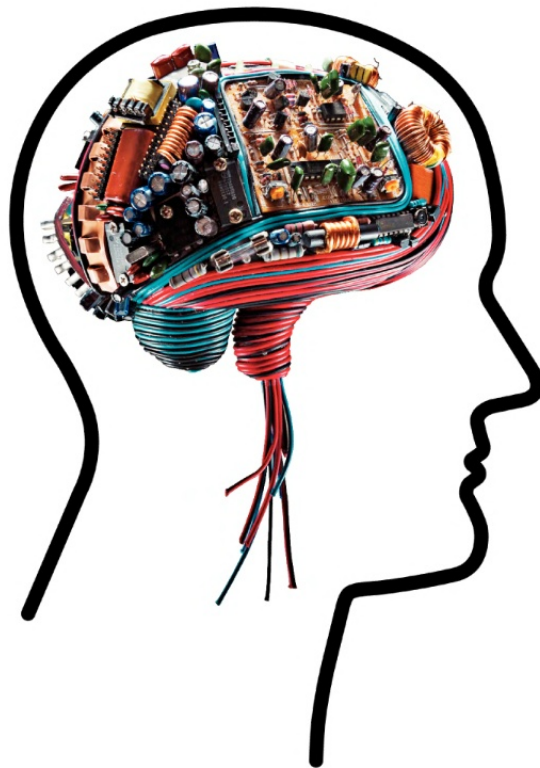


ANNALS OF MEDICINE

THE BODY ELECTRIC

A scientist takes computing power under the skin.

BY KIM TINGLEY



Ever since humans invented computer chips, we have dreamed of plugging them into us, or plugging us into them. And why not? A living body is inherently electrical: once every second or so, a dime-size bundle of cells in the upper chamber of the human heart produces an electrical pulse that keeps the organ beating, until the pulse ceases and we die. Cells shuttle ions in and out, communicating in a language tantalizingly similar to the positive and negative charges of electrical circuits. Eyes, ears, nose, tongue, skin—these are merely interfaces, ways for a body to chemically convert the uncharged outside world into current that, as it leaps through the brain, creates our thoughts and feel-

ings. In millivolts, we rue our limitations. If we could synch our synapses with man-made electronics, the thinking goes, we might ditch our bodies and become cyborgs, living forever as brains in jars, perhaps, or uploading our essential humanness to the Cloud.

The problem is physical: the body is soft, supple, and curved, but modern electronics, built on silicon computer chips, are rigid and flat, likely to shatter if dropped on a sidewalk. John Rogers, a shy-eyed materials scientist at the University of Illinois at Urbana-Champaign, likes to point out that, in 3.5 billion years, evolution has solved countless challenging problems without creating something that

looks like a silicon chip. “You think about the natural world, there’s a lot of rough and tumble,” he told me. “You have environments that are a lot less well-controlled than an iPhone case.” Researchers traditionally considered marrying electronics to biology using circuits made not from inorganic silicon but from pliable organic materials—the carbon-based building blocks of life. But current flows through these materials too slowly to power computers and gadgets. Rogers had another idea. In 2011, he and his colleagues announced the invention of a device that had hitherto seemed impossible: an integrated silicon circuit with the mechanical properties of skin.

In the journal *Science*, Rogers revealed what looked like a gold bar code—the circuit—set in a transparent layer of dried glue. Photographs showed it stuck to a postdoc’s forearm, so that its wires were visible, or hidden under a temporary tattoo that featured a pirate in a Fighting Illini hat. The circuit stretched and wrinkled when spread and pinched. It was waterproof and could harvest power from radio waves, which are emitted by cell phones, to measure skin temperature, pressure from swelling, hydration level, and electrical signals from the brain and heart. To otherwise gather this basic medical information in real time requires a person to be tethered to machines, limiting the ability to study the health or physiological performance of a soldier, say, or a ballerina, or an insomniac. A wireless medical patch would render obsolete much of the clunky diagnostic equipment in hospitals.

Rogers’s device, hailed as the first “epidermal electronics system,” caused a sensation. He received hundreds of e-mails from companies that hoped to collaborate: sellers of cosmetics, pharmaceuticals, sports drinks, and fitness equipment, along with fashion designers, “body artists,” state corrections agencies, the National Institutes of Health, the Defense Advanced Research Projects Agency, and the C.I.A. (This summer, after determining that Rogers has no demons that anyone could blackmail him with, the C.I.A. issued him a top-secret security clearance.) In the past several months, he has visited Boston, Dayton, Indianapolis, Nashville, Seattle, Washington, D.C., China, Germany, Korea, and Switzerland. “Everywhere we go, people want a

A new way of using silicon in the body may be about to shake up medical science.

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CONSTRUCTION BY MAURICIO ALEJO

ILLUSTRATION BY RICHARD MCGUIRE

device to put on the part of the human body they're studying," he told me.

The meeting of living systems and electronic systems is called "bioelectronics." In recent years, researchers have produced brain-computer interfaces that let users remotely control gadgets with their minds; retinal electrode implants that can restore limited sight to the blind; an ingestible sensor that, powered by stomach acid, lets patients monitor their response to medicine by means of a cell-phone app. But, arguably, no other research group has produced a class of devices that perform as well, cover as wide a range of potential applications, and are as close to being ready to use as Rogers's. He has more than a hundred patents and has co-founded six startup companies, attracting tens of millions of dollars in investment. A dozen of his flexible, stretchable devices are already in use in biomedical research; five more are on track to become commercial products. The first human clinical study to use Rogers's electronic-skin device, to evaluate wound healing, was recently completed. Another, examining sleep apnea, is under way.

In effect, Rogers has rethought silicon, a metalloid that, thanks to its abundance, low cost, and facility with binary bits, has become known among computer engineers as God's material. "He can look at a material and say, 'What can we do with it that's completely different from anything that's been done before?'" another bioelectronics engineer told me. "Suddenly this material that people have been studying for the past fifty years takes on a different role."

Collaboration has been crucial to Rogers's success. In October, Marvin Slepian, the director of interventional cardiology at the University of Arizona Sarver Heart Center, in Tucson, who works frequently with Rogers, invited me into his lab, where he produced a calf's heart in a plastic soup container, procured from a local grocer, and offered me a pair of latex gloves. The heart was slick and rubbery and about the size and shape of a human heart. Slepian set it in a tray and, with a scalpel, opened the upper chamber, the atrium. Inside, its walls were lined with squiggly folds. The tissue of the lower chambers, the ventricles, was pebbly. Stretched taut through the ventricles, from top to bottom, was a thicket of branching pink cords.

To locate arrhythmias—rogue electrical signals that can cause heart failure or

stroke—doctors snake a catheter through a patient's arteries and into this maze. The catheter has a silver tip, like a shoelace cap, typically with two electrodes on it. A skilled practitioner must poke two hundred points, in the course of two hours, to create a map of electrical activity. Doctors can use such a map to locate the source of an arrhythmia, and then they can sometimes insert another catheter to burn and destroy the site where the aberrant pulses appear to arise. But, since each signal is recorded at a different time, there is no way to watch a pulse propagate through tissue, which means that knowing where to burn is inexact.

Slepian then showed me a prototype of a new kind of catheter, which was built using Rogers's technology and is likely to be in hospitals within a few years. Instead of a metal tip, it had a deflated balloon coated with a crinkled-up integrated circuit that could support more than a hundred electrodes, plus other sensors. Slepian slipped the balloon into the heart and pumped it up. As it inflated, the circuit conformed to the organ's grooves and made contact with hard-to-reach tissue, enabling it to map a hundred electrical signals simultaneously, across a wider area and in far greater detail than had been previously possible. It also could be made to function in reverse, to apply precise burn treatment by delivering current instead of detecting it.

Rogers is so matter-of-fact about the potential for his devices and the details of how he'll assemble and test them that it sometimes seems as if the future had arrived a while ago and you were the last to notice. The first time I spoke with him, on the telephone, he described how people with heart problems will one day wear a self-contained "artificial pericardium," a filmy device that can be slipped over the heart like a sock. It will run on energy harvested from the organ's motion, monitor the health of individual cells, and correct irregularities by administering infinitesimal jolts through any of hundreds of electrodes or by delivering drugs held in the device's gelatinous, shadow-thin walls. (By comparison, the typical pacemaker—which has two electrodes that sit inside the heart and are attached by wires to a battery that is implanted in the chest and must be replaced every five to ten years—seems like a form of punishment.) Last fall, researchers at the Laboratory of Cardiovas-

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cular Engineering and Imaging, at Washington University, in St. Louis, slipped the device over a rabbit heart, beating with the help of a saline pump, and showed that they could gather measurements without disrupting the organ's movements. Thus wrapped, the heart looked like a strawberry with gold sensors for seeds. To simulate a heart attack, they stopped the flow of saline; the device mapped the loss of oxygen by measuring the tissue's pH level. Currently, people with heart-attack symptoms must wait for the results of a blood test to know for sure whether they are having one; if they are, their cells are already dying. The artificial pericardium will detect and treat a heart attack before any symptoms appear.

"It's twenty years or more out there," Rogers said. "But we can see a pathway—it's not science fiction." Bit by bit, our cells and tissues are becoming just another brand of hardware to be upgraded and refined. I asked him whether eventually electronic parts would let us live forever, and whether he thought this would come as a relief, offer evidence that we'd lost our souls and become robots, or both. "That's a good thing to think about, and people should think about it," he said. "But I'm just an engineer, basically."

Students joke that Champaign, Illinois, a college town surrounded by vast corn and soybean fields, is an ideal place to get a lot of work done. On a Tuesday in August, I met Rogers at seven-thirty at his office, in a red brick building on the edge of campus, where he arrives every

morning, except Saturday, at four o'clock. Downstairs, the door was unlocked, and the second-floor hallway, long and lit like an E.R., was empty except for a janitor mopping a men's bathroom. "It's nice, because it's quiet," Rogers said. "Nobody's around. By the time eight, eight-thirty rolls around, it's pretty much chaos."

Rogers, who is forty-six, has a perfectly straight nose and a helmet-shaped haircut. He was wearing an outfit that he seemed to have optimized: khaki trousers belted over a button-down shirt, its cuffs rolled up past his forearms, and a Casio watch that displayed the day of the week in giant letters. He had recently taken over the directorship of the university's Frederick Seitz Materials Research Laboratory and the office that came with it. The shelves were scattered with plastic models of organs mingled with awards plaques and certificates; he has won a MacArthur genius fellowship and a Lemelson-M.I.T. Prize, among other major accolades. On his desk was an outdated eight-by-ten of his son, who is now eleven, in a red sweater vest; a soda from Einstein Bros. Bagels; and noise-cancelling headphones, which he uses for listening to smooth jazz while he works. "I think what we do is jazz at some level, because we don't know exactly what we're doing," he said.

Rogers describes his breakthroughs as a series of happy accidents, as if he had regularly slipped on a banana peel and spied a trove of treasure through a crack in the floorboards. "I couldn't tell you what we'll be doing a year from now, cer-

tainly not five years from now," he said. A decade ago, he was the director of the condensed-matter-physics department at Bell Labs, in Murray Hill, New Jersey, where he worked on developing organic electronics that could be used to make roll-up-able televisions and computer screens. He had the bad luck to preside over the lab's first-ever case of fraud, committed by a young physicist in his department; an investigation cleared Rogers of any wrongdoing, but the incident helped persuade him to start over in academia. He realized that he wanted to engineer devices that could have a meaningful, immediate impact on society. He was still attracted to the challenge of making electronics flex and stretch, but he knew that, even if the devices he was working on could be perfected, it would take decades to assemble an industry to mass-produce them. Silicon integrated circuits already had billions of dollars in manufacturing facilities behind them. Using silicon in his electronics, Rogers figured, would let him quickly scale them up from handmade student models to something a factory could churn out.

Make anything thin enough, and it becomes bendy: wood turns to paper, metal to foil. Rogers recognized that integrated circuits, which are between one five-thousandth and one five-hundredth the width of a human hair, would flex if they could be separated from the chips they sit on. The chip, which is made of slightly thicker silicon, serves no electrical purpose; it simply supports the circuits as factories slice sheets of them apart and robotically maneuver them into devices. Rogers envisaged getting rid of the chip by building his silicon transistors on a hard substrate that could be selectively etched away by a chemical. "You might think that that's a readily solvable problem—you have a whole range of materials, just choose the right one," he said. But the substrate material had to be heat-resistant; circuits are baked at temperatures upward of two thousand degrees Fahrenheit. It also had to have an atomic structure similar to silicon's: semiconductors are grown as crystals in a vacuum chamber, and the substrate provides the initial template. In the process, the semiconductor and its substrate bond so tightly that separating the two with a third chemical is like trying to separate bark from a

INTERNET EPITAPHS



tree by setting the whole thing on fire.

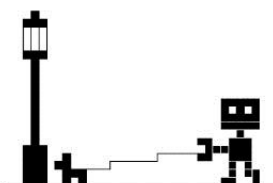
Eventually, Rogers figured out how to modify the surface of the substrate so that he could dip it in a chemical bath and rinse away nearly all of the top layer between it and a circuit without degrading the electronics. To keep the circuit temporarily in place, he let it remain anchored to its base at a few select points. Next, he wanted to use a rubber stamp to gently press and then lift the circuits, snap them from their anchors, and print them onto a new, flexible base. "You might say, 'O.K., I'll just make my stamp super-sticky, so even if the anchors are really tough I'll still pull them off when I pull my stamp away,'" he said. "That doesn't work because the devices adhere so strongly to the stamp that you can't get them off when you want to print them down on your substrate." It's like trying to wrap a gift using double-sided tape. He added ridges to the stamp, which reduced its area of contact, and modified its mechanics, applying the same law of physics that dictates that a Band-Aid ripped off quickly will cling less than one pulled off slowly. The result was a stamp that adhered just strongly enough to the circuits to yank them off the substrate, and weakly enough so that, once they were planted on their new base, the stamp could peel away and leave them behind.

Stretching was another matter. Silicon, no matter how thin, won't oblige. One day, a student who was building flexible devices told Rogers about a problem he was having. Sometimes, as the circuits pulled free from their anchors, the silicon buckled, making it difficult to get it to adhere to its new base. Nobody had previously discovered that property of silicon; Rogers realized that it could be his way around the material's inelasticity. He would fabricate silicon in accordion-like shapes that could unfold and fold without breaking: stretchability without stretching.

At first, Rogers thought that he would deploy his technologies outdoors. The military was interested in funding giant dish-shaped antennas that could fold up into a backpack, or X-ray machines that could wrap around the hull of a tanker. Then, in 2007, a doctoral candidate in bioengineering heard Rogers give a lecture at the University of Pennsylvania and asked him if he'd ever considered putting devices on the brain. He had not. "That

just seemed like a compelling direction," Rogers told me. "It was utterly obvious that we should be doing that."

Rogers is friendly, organized, and supportive, seemingly as much substrate as circuit. When I visited his lab, he handed me a typed, two-day itinerary, labelled in half-hour blocks, that mirrored his own. "Maybe before we go too far through the process I'll step you through the schedule to make sure you accomplish



what you need to accomplish," he said. I watched fourteen PowerPoint presentations given by students on devices-in-progress, listened to three conference calls with collaborating scientists, and talked with Rogers for several hours. I kept asking what inspired him and how he managed to find solutions to problems that no one else realized existed. "I think a lot of it has to do with persistence," he said finally. "It's not the case that I go on a bike ride and come up with a good idea. It's more that I'm thinking about it all the time. It's always kind of rattling around."

Rogers grew up in Sugar Land, Texas, a humid suburb of Houston. His father, John, Sr., worked for Texaco as a geophysicist. His mother, Pattiann, is a poet. As a child, Rogers played in bayous near his home, catching fish, frogs, and snakes. He was also fascinated with the sophisticated computers that his father used in his job. He finished high school early and spent the next year working in his father's office, using state-of-the-art processors to probe underground with sound waves, looking for oil. His father had been an Eagle Scout, and Rogers still wears a gold ring with a blue stone that he got when he earned his Eagle Scout badge, by building an elaborate locker facility for the community pool.

Rogers majored in chemistry and physics at the University of Texas and then went to graduate school at M.I.T., where, among other things, he used lasers to measure materials that, for various reasons, it is best not to touch. He built exponentially smaller, more precise laser

systems. "He would just show up in my office when a project was finished," his M.I.T. adviser, Keith Nelson, a chemist, told me. "I wouldn't even know about it until it had already been done." In Nelson's lab, Rogers met Lisa Dhar, a fellow materials scientist, and the two eventually married. After finishing his Ph.D., he decided to devote part of his final year to what he refers to as "the Super Bowl for M.I.T. geeks," a startup-business competition hosted by the university. He learned how to draft a business plan, and though his project, conceived around the new laser setups, didn't win, it did become a company, Active Impulse Systems. Three years later, in 1998, Philips bought the company, for an eight-figure sum that Rogers prefers not to name.

Professor-entrepreneurs aren't unusual at the University of Illinois, and Champaign itself harbors a surprising number of moguls, including a sandwich czar and the owner of the Jacksonville Jaguars; by these standards, Rogers insists that he's not wealthy at all. He drives a thirteen-year-old BMW and spends part of his minor fortune investing in his six companies. One, Semprius, uses the same stamping technique as his flexible devices do to print the world's smallest solar cells onto flat panels; the cells, made with gallium arsenide, a high-performance semiconductor, and coated with lenses the size of pinheads, are too small to handle with traditional tools. Recently, a prototype Semprius solar module set a record for efficiency, converting thirty-seven per cent of light into electricity. In principle, the cells could be printed on any surface: curved helmets, fabric tents.

Another company, MC10, focusses on fitness and medical applications. It recently launched its first commercial product, the Reebok CheckLight, a mesh skullcap designed to be worn while playing contact sports. Inside, it has a collection of accelerometers and a gyroscope to detect the force of blows to the head and L.E.D.s to indicate their severity, in red and yellow. The company, co-founded with Marvin Slepian, is also helping to develop the balloon catheter that Slepian showed me. Rogers says he saves the rest of his income to finance his research group in case of an emergency. "I have responsibility for these postdocs," he said. "A lot of them have families. I have to be able to pay their salary no matter what. So I've always

felt the need to have a sort of nest egg that I could draw upon, to support the group.”

Rogers doesn't work in the lab anymore. He supervises eighty undergraduate, graduate, and postdoctoral students, who carry out experiments he helps to design and report back to him. Often, as we listened to students and colleagues, his leg bounced and his fingers worried a nearby object—his keys, his pen. I asked him if he ever found it frustrating not to do experiments himself anymore. “It's great if you can do things with your own two hands,” he said. “But then you're limited by your own two hands, right?”

Still, sometimes he can't resist testing devices on himself. For a while, he travelled around wearing a dummy version of the epidermal electronic system, to see what it felt like and to show it off. As a demonstration vehicle, he said, “it tended to be really effective, because people would come up after talks and rub their finger across the device on my skin and get a more intuitive feeling for the kinds of technologies we're working on.” The device would stay on for a week and a half, even with a daily shower; it helped if he added a new coat of Walgreens spray-on bandage each morning. “But my students were going crazy, because they have to build them by hand,” he said. “So I had to stop doing that. But you can get through a metal detector, no problem.”

Rogers was trained in the so-called hard sciences, but the more time he has spent with the spongy materials of biology the more he has wanted to get his devices deep inside tissue. A couple of years ago, researchers at the Litt Lab, at the University of Pennsylvania, tested a device, designed with Rogers, on an epileptic cat. Studying epilepsy typically involves temporarily removing a portion of a subject's skull and placing metal electrodes, each embedded in plastic and hooked up to individual wires, on the brain's surface. But the approach can accommodate no more than a hundred and fifty electrodes. Rogers designed an array of three hundred and sixty flexible electrodes, collectively smaller than a postage stamp, that melds into the brain's folds, achieving better contact and resolution. In testing the array on the cat, the researchers discovered that electrical activity arose in advance of seizures from much smaller areas and in more complicated electrical patterns than they had previously thought. Coming ver-

HUMMINGBIRDS

I thought she was exaggerating a little when she said that every one of her hummingbirds—she had five—had a distinct name and that they flew freely in her garden, where they had distinct feeders. “If not, they fight too much.”

But it was like that, just like that: I saw them once, when the house, alone, invited a visit to the open back garden.

There they came flying like tiny winged envoys with urgent notices and warnings. No name fit them well. Useless words. Astonishment at the rapid movement of the wings: the not being able to look at them the approach of their tiny hearts beating so incredibly rapidly close, very close,

and then suddenly shooting off, high, unattainable. Beings of our world but also of another, only theirs.

—Circe Maia

(Translated, from the Spanish, by Jesse Lee Kercheval.)

sions of the device will slide in through a small hole in the skull, unroll over the brain, detect unusual activity, and potentially treat it with precise electrical pulses.

But most of what goes on in the brain happens below the surface. Lately, Rogers has been following the emergence of a new research field called optogenetics, which entails threading light-emitting devices into the brain to trigger neurons with photons. It is the most precise method yet for exploring how exact constellations of neurons affect behavior—which unique pattern of synaptic firings permits one's fingers to close around a friend's hand, sense her touch, and generate a sense of comfort—and how to manipulate them. The first step, using a virus to gain entry, is to infect a specific group of brain cells with a protein that makes them sensitive to light. Then a fibre-optic cable is implanted next to the cells, to beam in photons. Turning on the light activates the cells, while neighboring cells are unaffected—a feat of spatial and temporal precision impossible to achieve with drugs

or electrical stimulation. Delivering light to the brain means tethering subjects—just mice, for now—to a cumbersome fibre-optic cable that is fastened to a light source. This has limited a mouse's mobility, sabotaging its social life and making it difficult to parse the behavioral effects of turning certain neurons on and off.

Rogers may have solved this problem, too. With neuroscientists at Washington University's Bruchas Lab, he designed a flexible, wireless L.E.D. far thinner than an eyelash. Its antenna is a cube that the mouse wears like a tiny top hat, secured with denture paste. The antenna receives signals that operate the light and harvests the power to run itself from radio waves. The researchers concentrated on a cluster of the mice's neurons that they knew released dopamine, a neurotransmitter that confers a pleasurable sensation. They infected them with the protein that would make them react to light and implanted Rogers's device a few microns away. After a month of recovery, the mice were let loose in a Y-shaped maze. If they poked

a button at one end of the maze with their nose, it sent a signal that turned on the light in their brain and triggered a rush of dopamine; if they poked buttons at the other ends of the maze, the light stayed off. In the study, the mice returned obsessively to the dopamine button: they had gained, and liberally employed, the ability to wirelessly activate neurotransmitters that made them feel good. Similar implants in people might one day offer patients a way to activate their own neurotransmitters to alleviate pain, epileptic seizures, Parkinson's tremors, and disorders such as addiction and depression, without employing drugs, electroshock, or the removal of brain tissue.

One afternoon, Jordan McCall, a bearded graduate student at the Washington University School of Medicine, and Ream al-Hasani, a postdoctoral fellow with a soft British accent and turquoise fingernail polish, let me watch as they implanted in the brain of a mouse a device that their lab had designed with Rogers. The mouse lay on a platform, its nose positioned at the mouth of a tube delivering a combination of oxygen and anesthesia. The plan was to use the device, which had two L.E.D.s, to study two groups of neurons in a region called the nucleus accumbens, which humans also possess. Though the groups were situated less than a millimetre apart, they appeared to have opposite roles; activating one group should produce a rewarding sensation, while activating the other should produce an unpleasant one. Given their proximity to one another, their roles can't be teased apart using drugs, electricity, or a scalpel.

With his thumb and forefinger, McCall lifted the device they were implanting from a petri dish: two translucent L.E.D.s hung from a plastic cube the size of a die—the mouse's top hat. Alongside each one was an electrode to measure neural signals and a temperature sensor to make sure that it wasn't overheating the brain. Each strand was virtually invisible, about the size of four mouse brain cells. The strands would cause far less inflammation than typical, stiffer fibre-optic cables do. "The bad news is, it's so flexible and floppy that it doesn't have the rigidity needed to penetrate the brain tissue in the first place," Rogers told me. To push it in, he had mounted the L.E.D. on a needlelike polymer base, using a thin film of silk glue that would dissolve in brain fluid. The re-

searchers could lower the needle and L.E.D. into the brain, wait fifteen minutes for the silk to dissolve, and then pull out the needle, leaving the device behind.

McCall clamped the polymer needle in a mechanical arm and lowered it and the electronics gingerly into the mouse's brain through a hole drilled in its skull, watching the device's x, y, and z coordinates on a monitor. "Looks like the flexible part is not cooperating," he said. The silk glue had come loose as the needle entered the brain, and one of the L.E.D.s had bent and caught on the surface tissue. McCall tried a second device, which slid into the brain as planned, but the antenna slipped from his grip before he could secure it with paste. "I'm sorry, gravity worked against us," he said. "That was user error, not design error." To avoid damaging the mouse's brain, he aborted the experiment.

Later, I called Rogers and told him what had happened. He was philosophical. "I think ninety-nine per cent of the experiments one does are failures," he said. "One of the frustrating aspects of academic, discovery-based research is that the minute you figure out how to do things repeatedly and reproducibly, you immediately go on to something else." Even so, he hated it when a device broke. When I visited his lab, I'd remarked on how delicately his students packaged their creations, nesting them in petri dishes on beds of foam. He said that he'd suggested this, in part, to encourage outside clinicians and researchers to handle them gently. "The devices need to be able to operate in the hands of people who didn't build them," he said. "Inevitably, they're way rougher on them than they'd be if they'd made them. They're precious things, but you hand them off to some other guy and he's tossing them around."

As scientists continue mapping the brain and its billions of connections, they are finding new ways to electronically tweak them to fix the body's failings. People who have lost their hearing because they've damaged the hair cells in their ears, which normally mediate the perception of sound, can turn to cochlear implants that send electrical signals straight to the auditory nerve. Last year, researchers for the company BrainGate released a video of a woman who has been paralyzed for fifteen years by a brain-stem stroke. With a brain-machine interface, and using just her thoughts, she directs a robotic arm to lift a

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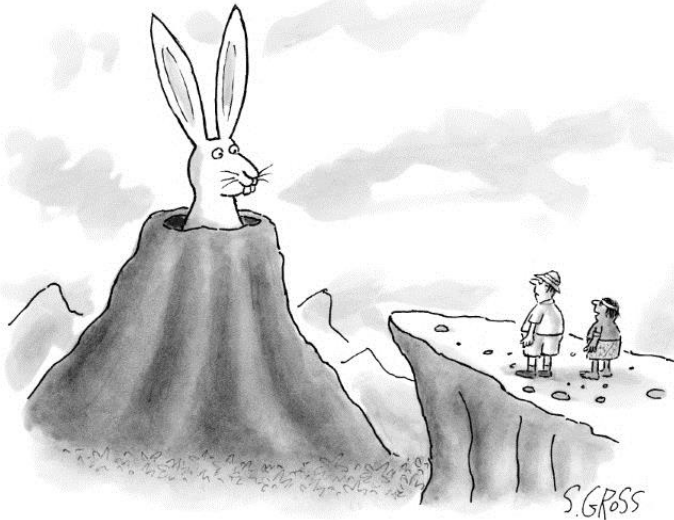
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Seen it?

THE NEW YORKER, NOVEMBER 25, 2013

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"We keep it simple. That's our god of fertility."

bottle of coffee to her lips so she can sip it through a straw. At the 2014 World Cup, the ceremonial kickoff will be made by a paraplegic wearing a robotic "exoskeleton," operated with EEG sensors taped to his or her scalp. "You'll see these new prosthetics and new technologies to treat psychiatric and neurological disorders come very soon," Miguel Nicolelis, a neuroscientist at Duke University and the device's designer, told me. "You'll be part of the computer literally. You're going to be embedded into your operating system by using your brain both to control the operating system and to receive feedback from it."

Eventually, as we gain the ability to hot-wire individual neural circuits, our senses could be enhanced as well as repaired. Michael McAlpine, a nanotechnology engineer at Princeton University, recently created a bionic ear by 3D-printing flexible electronics and cartilage; it can detect frequencies that no biological ear, human or other, can hear. "If you think of all the different animals on the planet, they all have different ranges of capabilities," McAlpine told me. "For instance, a dog can hear at higher frequencies than a human. Being able to turn the human into a universal animal that can do all those things would be kind of cool, I think."

One afternoon, I asked Rogers if he had any interest in becoming a universal animal. We were in his office, where he

was waiting for a call. In the hallway, a coffee tureen had drawn a crowd, and the smell of the coffee and the sound of voices drifted in. "I wouldn't argue with that vision," he said. "But I think for things to go on the brain, at least in my lifetime, it has to be pretty compelling. If someone is dying or someone is suffering from severe epilepsy, that's reason enough to take your skullcap off. But to see in the dark—probably not."

Rogers's next idea is "transient" electronics: devices that, after a set period of time, when their task is accomplished, melt away in the body. It turns out that silicon, if made thin enough, can not only flex but dissolve. Last year, in *Science*, Rogers described circuits with bases made of silk, magnesium wires, and super-slim silicon transistors—materials that are compatible with human tissue and can be set to dissolve on a timetable determined by their thickness and purity. His lab is experimenting with several polymers to create adhesives and coatings that can degrade safely in the body. Five are already F.D.A.-approved.

"We don't fully know what transient material is going to be good for, but there's no shortage of stuff for it to do," he said. "Dissolving brain implants, monitoring devices. We're working with a couple of people on drug delivery systems; once the drug

is gone, you'd like the delivery system to disappear. That kind of thing." He showed me a handout listing potential applications, some of them of interest to the C.I.A. "We're only funded for this one," he said, pointing to a line that said "XXXXXX-XX."

One evening, Rogers and Dhar held a dinner party for a visiting delegation from his company MC10, which is based in Cambridge, Massachusetts. They live in a modest two-story house, in a subdivision built around an algae-covered lake. Inside, the living room was cheerfully decorated with tawny leather furniture and a ficus with an origami crane hanging from a branch. Dhar had made salad, roast beef, and quiche. As we sat down, she scolded Rogers for stealing away to the living room with his laptop to show two of the MC10 employees a video that some researchers from the N.I.H. had sent him. It showed the temperature ("not 98.6 but 98.695," he noted) changing in the sweat glands of a thumb. Gathering the measurements had been painstaking, requiring a person to sit perfectly still in front of a giant camera, but they could be quickly and easily made with Rogers's epidermal system, he told me. After dinner, Rogers passed out cherry pie and ice cream. Before the guests dispersed, he put a new bulb in a burned-out driveway light so that his son, John III, could play a game of pickup basketball with MC10's head of sports, a former N.F.L. linebacker. John, a thin fifth-grader with a sly smile, was eye level with his rival's navel and only slightly wider than his biceps. The sound of the ball on the pavement echoed through the neighborhood. Rogers stood in the driveway, apart, arms crossed, watching.

Rogers believes that we should think about electronics not as something inanimate and foreign but as part of us. Last December, at the annual International Electron Devices Meeting, as he was preparing to present his transient circuits for the first time, a colleague suggested that he eat one onstage. "It was a little nerve-racking," Rogers said. "By practicing beforehand, I figured out that the key is to suck on it, not chew it. You just let it dissolve on your tongue and wait it out a few seconds and then you can swallow it." He now believes that his performance was in questionable taste—too showy, and a poor model of behavior for students who might imitate him—and says that he'll think twice before doing it again. ♦