In 2001, scientists assembled molecules into basic circuits, raising hopes for a new world of nanoelectronics

Molecules Get Wired

Computer chip technology and scientific breakthroughs have been marching in step for decades. Without computers, scientists couldn't track climate change, sequence the genomes of entire organisms, or image the human brain at work. But the ability to cram ever more circuitry onto silicon chips now faces fundamental limits. Ironically, it's now possible to make the innards of a circuit—the transistors, resistors, capacitors, and wires—so small they no longer function.

Breakthrough Online
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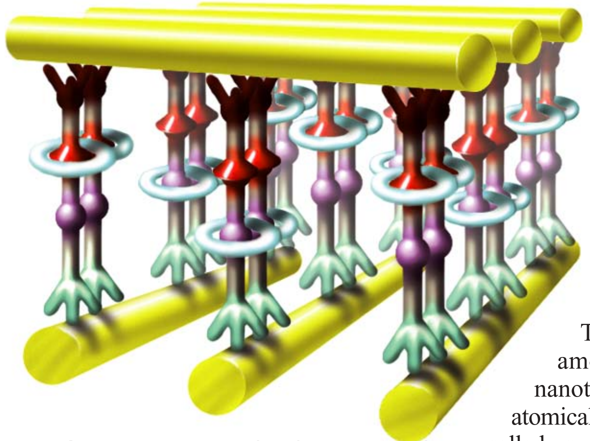
In recent years, scientists have tried to get around these limits by going for the ultimate in shrinkage: turning single molecules and small chemical groups into transistors and other standard components of computer chips. It's a provocative idea, but many have doubted that researchers would ever manage to link such devices together into more complex circuits. Today, those doubts are diminishing. This year, researchers wired up their first molecular-scale circuits, a feat *Science* selects as the Breakthrough of 2001. If researchers can wire these circuits into intricate computer chip architectures, this new generation of molecular electronics will undoubtedly provide computing power to launch scientific breakthroughs for decades.

It's easy to see the allure of computing with molecules. Today's state-of-the-art computer chips pack some 40 million transistors onto a slab of silicon no bigger than a postage stamp. The smallest features in these miniature landscapes measure just 130 billionths of a meter, or nanometers, across. In another 10 years or so, chip engineers expect to shrink whole transistors—not just individual features—down to about 120 nanometers per side. Small as this seems, it's still gargantuan compared to molecules, which are some 60,000 times smaller. Chips made with components at that scale would harbor billions of devices.

Dreams of such unbridled computer power started soon after the dawn of the computer age itself. In 1974, Mark Ratner and Ari Aviram of IBM suggested building computers from the bottom up by turning individual molecules into circuit components. But their suggestion remained little more than a pipe dream until the advent of scanning probe microscopes in the 1980s, which gave researchers the tools to probe individual molecules and move them around at will. That led to a spate of studies in the late 1990s that showed that individual molecules could conduct electricity like wires or semiconductors, the building blocks of modern microprocessors.

Turning individual molecules into devices was not far behind. In 1997, groups led by Robert Metzger of the University of Alabama, Tuscaloosa, and Chong-Wu Zhou of Yale University created molecular diodes, one-way current valves that are among the most basic and essential elements in the chip designer's tool kit. In July 1999, another group led by James Heath and Fraser Stoddart of the University of California, Los Angeles (UCLA), created a rudimentary switch, a molecular fuse that carries current but, when hit with the right voltage, alters its molecular shape and stops conducting. Within months, still another team led by Yale University electrical engineer Mark Reed and Rice University chemist Jim Tour reported making molecular-scale devices that could control a current just as a transistor does.



Good connections. Molecules can now be crafted into working circuits. Constructing real molecular chips will be a big challenge.

By the end of 2000, researchers had amassed a grab bag of molecular electronic devices but no demonstrations of wiring them together. 2001 brought a world of difference, when five labs succeeded in hooking up these devices into more complex circuits that could carry out rudimentary computing operations. In January, a team led by Charles Lieber, a chemist at Harvard University, got the ball rolling. In the 26 January issue of *Science*, Lieber's team reported arranging indium-phosphide semiconducting nanowires into a simple configuration that resembled the lines in a ticktacktoe board. The team then used a technique called electron beam lithography to place electrical contacts at the ends of the nanowires in order to show that the array was electronically active. The tiny arrangement wasn't a circuit yet, but it was the first step, showing that separate nanowires could communicate with one another.

The next step came at the American Chemical Society meeting in April. Heath and his colleagues at UCLA reported making semiconducting crossbars. But in this case, Heath's team placed molecules called rotaxanes, which function as molecular transistors, at each junction. By controlling the input voltages to each arm of the crossbar, the scientists showed that they could make working 16-bit memory circuits.

But molecular crossbars were only part of the success story. Researchers also made heady progress with their favorite nanomaterial, carbon nanotubes. These tiny straws of carbon are among the hottest materials in the nanotech world because they have an atomically perfect structure, resembling a rolled-up sheet of chicken wire. Depending on how these carbon sheets are rolled—so that chains of carbon atoms circle or spiral around the tubes—the nanotubes' electrical properties can be engineered to serve as either conductors or semiconductors.

In the 26 August online edition of *Nano Letters*, a team led by Phaedon Avouris of IBM reported making a circuit out of a single semiconducting nanotube. By draping the nanotube over a pair of electrodes and independently controlling their behavior, the team coaxed the device to work like a simple circuit called an inverter, another basic building block for more complex circuitry.

In addition to carrying out rudimentary processing, the IBM circuit demonstrated another key advantage: "gain," the ability to turn a weak electrical input into a stronger output,

ILLUSTRATION: C. SLAYDEN

The Year of Living Dangerously

When the World Trade Center towers collapsed on 11 September, seismographs recorded an impact equivalent to that of a mild earthquake. The aftershocks for the international science and engineering community, however, could be of much greater magnitude—from reshuffled budgets to new restrictions on research, information-sharing, and international collaboration. Indeed, some scientists say the terrorist assaults, and the subsequent anthrax mail attacks, could mark the beginning of a sobering new era of scientific soul-searching, akin to that which followed the development of the atom bomb.

The new landscape "will present some scientists with opportunities and others with obstacles," says Lewis Branscomb, a science policy specialist at Harvard University, who is helping lead a U.S. National Academies study of what scientists can do to respond to terrorism.

The immediate consequences of the attacks were far-reaching. Engineers analyzed why the towers fell—and debated what should be done to make skyscrapers safer. Gene researchers scrambled to cobble together a DNA-testing system capable of generating and handling the cascade of data needed to identify the thousands of crushed and incinerated victims. Public health specialists struggled to identify and treat those threatened by anthrax. Microbiology sleuths took to their labs, hoping to finger the deadly strain's origin.

The U.S. Congress, meanwhile, passed sweeping new security laws requiring everything from the installation of new security technology at airports to criminal background checks for scientists working with deadly biological agents. It debated barring foreign students from studying certain sensitive scientific topics at U.S. universities. And lawmakers pumped billions of new dollars into developing ways of detecting biowarfare agents—and creating new vaccines that could render them harmless. Other nations, such as the United Kingdom, launched similar initiatives.

The shake-up is far from over. Economic damage caused by the attacks has erased a U.S. government budget surplus, raising fears that some research spending might be trimmed next year to pay for the war against terrorism. Universities are reconsidering research programs involving potential bioweapons in light of increased regulation and community concerns. Journal editors, research funders, and scientists have begun debating whether some information—such as the genomic details of candidate bioweapons—is just too sensitive to be released publicly. "If the scientific literature is no longer used for the good it was intended, we will be left with no choice but to restrict information access at a cost to human health," *The Lancet Infectious Diseases* warned in a 1 December editorial.

Many researchers hope such crackdowns can be avoided. But they are again pondering how to work for good while keeping the fruits of their labors from being used for evil.

–DAVID MALAKOFF

Shake-up. Twin Tower and anthrax attacks have rattled the science community.

which is a necessary feature for sending signals through multiple devices. Circuits with even stronger gain came just over 2 months later in a pair of reports in the 9 November issue of *Science*. The first, by Cees Dekker's team at Delft University of Technology in the Netherlands, also relied on carbon nanotubes. In 1999, Dekker's group was the first to report making a nanotube-based transistor. His team then wired up a range of logic circuits with nanotube-based transistors. By carefully controlling the formation of metal gate electrodes, Dekker's group was able to create transistors with an output signal 10 times stronger than the input. Lieber's group at Harvard, meanwhile, constructed circuits with their semiconducting nanowires, in this case made from silicon and gallium nitride.

Finally, in a report published online by *Science* on 8 November, a group led by physicist Jan Hendrik Schön of Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey, reported similar success in crafting circuits from transistors made from organic molecules that chemically assemble themselves between pairs of gold electrodes.

Backed by this string of accomplishments, molecular electronics is rapidly moving from blue-sky research to the beginnings of a technology. Experts in the field have few illusions, however, that molecular electronics will replace conventional silicon-based computing anytime soon, if ever. Researchers now face the truly formidable task of taking the technology from demonstrations of rudimentary circuits to highly complex integrated circuitry that can improve upon silicon's speed, reliability, and low cost. Reaching that level of complexity will undoubtedly require a revolution in chip fabrication. But as chip designers race ever closer to the limits of silicon, pressure will to extend this year's breakthroughs in molecular electronics will only intensify.

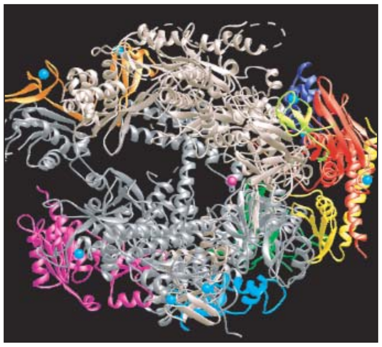
–ROBERT F. SERVICE

THE RUNNERS-UP

Science celebrates nine other areas in which important findings were reported this year, from subatomic to atmospheric and beyond.

First runner-up: RNA ascending. RNA molecules, long viewed as little more than couriers shuttling messages or amino acids around the cell, are turning out to be remarkably versatile. In 1995, researchers showed that small pieces of RNA could shut down genes in the nematode *Caenorhabditis elegans*, a phenomenon very similar to gene silencing, which was known to occur in plants. Molecular biologists realized that this RNA interference (RNAi) could be a boon to studies of gene function, and now interest in RNA has exploded. This year, they discovered that RNAi can quell gene activity in mouse and human cells as well.

Short RNAs clearly play important biological roles. Dozens of the



Structure solved. RNA-building enzyme revealed.

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