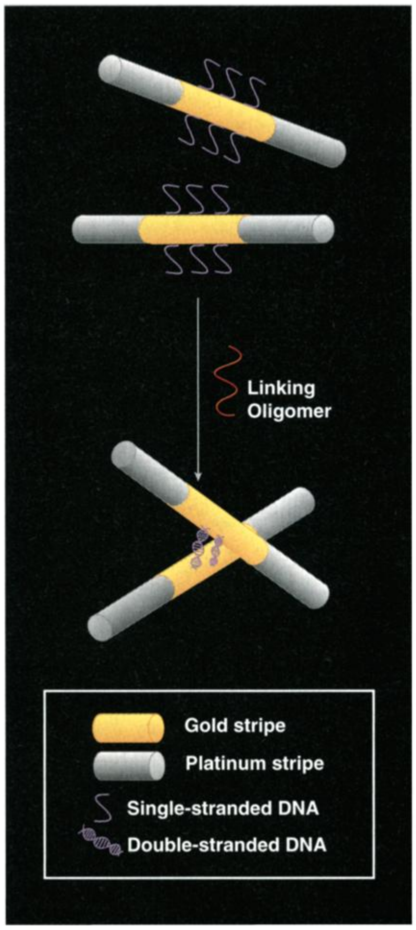
Yet Another Role for DNA?

As they struggle to join nanotubes and nanowires into simple X shapes, molecular electronics researchers dream of making much more complex circuitry. "Everybody is trying to make larger arrays" of devices, says Tom Mallouk, a chemist at Pennsylvania State University, University Park. "What we're seeing now is just the beginning." To move from the simple to the complex, though, scientists will need to develop a much defter touch.

Some think the key to that dexterity lies in that consummate molecular sleight-of-hand artist, DNA. By taking advantage of DNA's ability to recognize molecules and self-assemble—not to mention the huge toolkit of enzymes and techniques biologists have developed for working with the molecule—they hope to use DNA as a template for crafting metallic wiring, or even to wire circuits with strands of DNA itself.

Mallouk's group, also led by chemist Christine Keating and electrical engineers Tom Jackson and Theresa Mayer, starts by growing metal nanowires in the tiny pores of commercially available filtration membranes. Because the researchers can vary the composition of the metals laid down in the pores, they make nanowires with one type of metal, such as platinum, on the ends, and another metal, such as gold, in the middle. By attaching gold-linking thiol groups to single-stranded DNA, they can bind the DNA to the gold midsections of the nanowire. To coax the nanowires to assemble into different shapes, they simply attach complementary DNA strands to the gold segments of other nanowires. The complementary strands then bind to each other, welding pairs of wires together.

In initial experiments, the team has used the technique to make simple shapes such as crosses and triangles. And they are currently using it in an attempt to assemble more complex circuitry, Keating says: "You can envision using this to carry out the deterministic assembly of a circuit." That hasn't happened yet, in part because the DNA on some nanowires tends to bind indiscriminately to other noncomplementary DNA rather than its partner strand. But because biochemists have learned to solve this problem with applications such as DNA chips, Keating is confident that DNA will soon become a type of addressable glue for a wide variety of molecular electronics components.



Matchmaker. A piece of single-stranded DNA links corresponding sequences on nanowires to forge a cross.

Erez Braun and his group at the Technion–Israel Institute of Technology in Haifa take a different approach. Instead of using DNA to join wires together, they make wires by silver-plating DNA itself (*Science*, 20 March 1998, p. 1967). The researchers start with a pair of gold electrodes 1200 nanometers apart on a sheet of glass. First they attach snippets of DNA 12 oligonucleotides long to each electrode. Then they immerse the electrodes in a solution containing short lengths of viral DNA. The viral DNA attaches itself to the snippets, creating a DNA bridge between the electrodes. Next, by soaking the bridge in a solution containing silver ions, Braun and colleagues coat it with silver. The result is a nanometer-scale metallic wire between the electrodes, with properties that can be varied by fiddling with the developing conditions.

Braun says they have extended the approach and are now close to completing a three-terminal switching device that would function much like a transistor. They are also studying how they might scale up these processes to create more complex networks.

More exotically, it's even possible that wires might be made of DNA itself. First, though, researchers will need a much better understanding of DNA's basic electrical properties. Since the first report, in 1993, that DNA can carry current, measurements of its conductivity have ranged from zero, a perfect insulator, to superconductivity when the electrodes are spaced very closely together. Christian Schönenberger, a physicist at the Swiss Nanoscience Center in Basel, says most researchers now think that DNA is a semiconductor whose conductivity depends on how it is "doped" with foreign molecules. The wide range of conductivity is good news, Schönenberger says. "It means that we can, in principle, tailor the doping and control the conductivity." To make electronic devices, though, scientists must sort out precisely which parts of DNA's complex chemistry do the doping—and that may be no simple task.

—D.N. AND R.F.S.

neers can make features close to 100 nanometers across, and they're already eyeing a version of the technology that could cut that in half (see p. 787).

Molecular electronics has the potential to go much smaller, with components composed of just tens or hundreds of molecules. That would clearly accelerate the march of Moore's Law. But it could do much more as well. For one, it might solve a problem that is already beginning to vex chipmakers: heat. Wires carved into silicon by the standard technique of lithography are riddled with imperfections along their edges. As wires shrink, electrons coursing through them run an ever greater chance of smashing into one of these defects and generating unwanted heat. Pack too many circuits onto a chip and you get burnout. Lacking such imperfections, molecules such as nanotubes are expected to do a better job of preventing electrical losses as well as containing electrons that travel along their lengths.

Perhaps most important, a shift from silicon to molecules could also break Moore's Second Law, a corollary to the first, which states that the cost of new chip-fabrication plants increases exponentially as the features get smaller. By 2015, experts suggest, they will cost somewhere between $50 billion and $200 billion apiece. Because molecular electronics relies on molecules to assemble themselves rather than on lithography, self-assembly "is likely to beat [Moore's Second Law] before it beats the first," says Mallouk. Adds Mark Ratner, a chemist at Northwestern University in Evanston, Illinois, and one of the fathers of the field: "It's cheap to make molecules. It's expensive to make fabs."

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