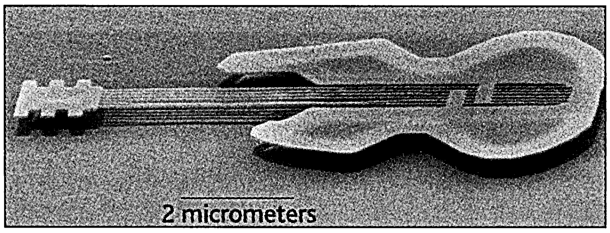
physics and chemistry, one has to know the real possibilities."

And of course, experimental science is constantly expanding the scope of what is feasible. Whitesides and Stephen Chou of Princeton University have recently pioneered a new rubber stamping method for patterning surfaces with features as small as 10 nanometers. That is well below the current size limit of about 200 nanometers faced by photolithography, the primary patterning tool used by the computer chip industry. Still, the stamping technique has its own drawbacks: It has trouble patterning multiple materials in three dimensions, as is needed for making computer chips, and ensuring proper alignment of all the various layers of material.

Another patterning alternative making headway is a burgeoning subfield of chemistry known as self-assembly, in which researchers design materials to assemble themselves into desired finished structures. For example, last year IBM researchers led by chemist Christopher Murray came up with a way to make metallic particles as small as 3 nanometers and then assemble them into a three-dimensional array. Such structures could lead to material for future computer disks in which each nanoparticle stores a bit of data. Still, for now such successes tend to be the exception rather than the rule.

Future nanoapplications face other grand challenges as well. Even if particular nanocomponents can be mass-produced, researchers will still need to figure out how to position them on surfaces or other structures so they can be used as components in electronic devices, sensors, and the like. For tiny electronic components, researchers will then face the major stumbling block of wiring them up to the macro world.



Nanocaster. World's smallest guitar, with strings 100 silicon atoms wide, is huge by the latest nanostandards.

They will also confront the more mundane challenge of connecting with one another. By all accounts, nanotechnology will require an extraordinary range of expertise. Researchers have long embraced the concept of interdisciplinary research. And organizations such as the NSF make it a point to finance interdisciplinary centers. Still, academia remains largely hidebound in disciplines, making it difficult to pursue research that falls between traditional fields. "There still exist many elements in the culture of our research universities that discourage multidisciplinary research," says James Merz, the vice president for graduate studies and research at the University of Notre Dame in Indiana.

Among the chief culprits Merz points to are the administrative autonomy given to separate departments and the fact that faculty members must obtain tenure from specific departments. Furthermore, Theis points out, essentially no curricula have been developed to train future researchers in the field, let alone degree programs to turn out new nanotech Ph.D.s. Although those impediments aren't necessarily fatal, they can easily hamper the field's development, Merz says.

Beset by such challenges, nanoreality is bound to fall short of nanohype. The danger is that disenchantment with the gap could dampen financial support for the field, says Mihail Roco of NSF, who heads the U.S. National Nanotechnology Initiative. That's a scenario well known to researchers in high-temperature superconductivity, an enterprise that has struggled to live up to the fanfare that greeted it in the mid-1980s. Still, unlike superconductivity—a narrow field whose impact is limited to a comparatively small sphere of applications—nanotechnology is likely to benefit from its breadth, says Srivastava. "Since the net is much wider," he says, "the chance is bigger that you will catch some fish."

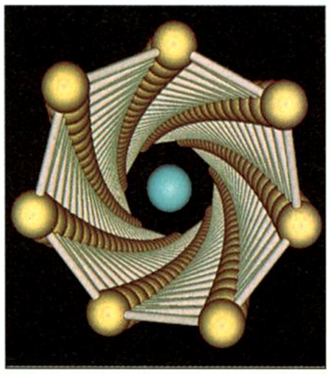
–ROBERT F. SERVICE

Strange Behavior At One Dimension

TOKYO—For Kunio Takayanagi, a physicist at the Tokyo Institute of Technology, thinner is better. Takayanagi has calculated that electrons should pass through the 1-nanometer gold wires he has crafted at speeds several orders of magnitude faster than those at which they pass through larger wires. If such wires could be fashioned into circuits, they could set the stage for even faster supercomputers. "In electronic device technology," he says, "the speed of the electron is the most important thing."

Such high speeds are made possible by the internal structure of the nanowires through which the electrons pass. "At larger scales, materials form crystals," explains Erio Tosatti, a theorist at the Institute for Theoretical Physics in Trieste, Italy. "In the nanowires, the material is not a crystal. It is very different, electrically and mechanically."

Takayanagi was the first to determine this structure by putting a miniaturized scanning tunneling microscope (STM) within an ultrahigh-vacuum, high-resolution transmission electron microscope (TEM). By irradiating a thin gold film with an electron beam, he reduced it to a wire. Imaging with the TEM and the STM revealed that when the wire was thinned to a diameter of roughly 1 nanometer, atoms organized themselves into nested tubes, with the atoms in each tube arranged in a helix coiled around the wire axis. The structure is akin to that of carbon nanotubes.



Twister. Spirals of gold, 1 nm across, may rev electrical currents up to record speeds.

Takayanagi's prediction of the speed of electron transport is based on some preliminary conductance measurements and theory. Theory suggests that the electrons would move so efficiently that no heat would be generated. Groups at Nagoya and Osaka universities in Japan and at Leiden University in the Netherlands have produced similar wires and plan to measure some of their mechanical and electrical properties.

In addition to the obvious advantages for the electronics industry, the work has important implications for basic science. Pointing to the helical structure of carbon nanotubes and the double helix of DNA, Takayanagi says it's possible that "all material will take on a stable helical structure if it is one-dimensional like a nanowire." Tosatti is equally excited. "I think this work could lead to an understanding of how matter spontaneously organizes itself at the nanoscale," he says.

–DENNIS NORMILE

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