outer layers. Such a map could yield new information about temperature and density in the photosphere, the thin overlying chromosphere, and the extended corona.

Another experiment, done at NASA's 3-meter infrared telescope, also relied on the moon as a knife edge, in this case to pinpoint an emission line from ionized magnesium. The intensity of the line traces the strength of the sun's magnetic field, and by recording infrared signals during the occultation the investigators hoped to map the emitting magnesium. But before and after totality the telescope's large mirror would also act as a solar collector, cooking the instruments at its focus. So the NASA scientists covered the dish with the white plastic usually used for potato-chip bags, which lets infrared through but blocks sunlight. NASA-Goddard astronomer Donald Jennings called it a great moment for the packaging industry.

Meanwhile, the optical astronomers planned to use the mountain's big mirrors, the UH 2.2-meter and the Canada-France-Hawaii 3.6-meter telescopes, to make movies of the corona. By snapping many frames per second on video and movie film, they hoped to capture in freeze-frame the mysterious mechanism that heats the corona to a million degrees K just a few hundred kilometers above the sun's visible edge, the photosphere, where the temperature rises no higher than 5800 K.

All these projects hung in the balance as the clouds surged around the mountaintop and the moon's shadow raced eastward across the Pacific toward Hawaii. Luckily, the clouds below stayed put through the four minutes and 12 seconds of totality. The sight was sensational; Hall called the corona "ten on a scale of ten" for sheer naked-eye spectacle. A large prominence—a glowing-red streamer of photosphere erupting above the solar limb—wreathed the occluded sun. To the electronic eyes of the telescopes, the eclipse, fuzzed somewhat by the volcanic haze and the cirrus, was less spectacular but satisfactory, astronomers said.

In the case of the infrared search for the dust ring, Hall was able to report within days that "the data were really superb." They don't tell an entirely welcome story, though. "Unfortunately, they don't seem to show any dust rings at all."

Most of the other results will be weeks or months in coming. But outside the telescope domes, eclipse-watchers wasted no time in giving a verdict. As the moon's shadow fled eastward toward Baja California, and the sun's brilliance returned, the crowds burst into applause. ■ CHARLES PETIT

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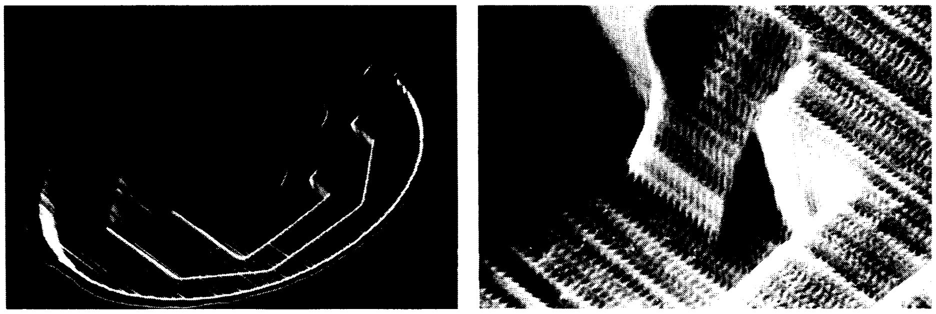


Ehrlich and Bloomstein

Fine handiwork. *A microscopic pit carved in silicon by Lincoln Laboratory's CAD/CAM system. The contours of the structure were chiseled one "volumetric pixel" at a time* (right).

The Small Wonders of Microengineering

As technoshrinkers get better at miniaturizing sensors and mechanisms, they are pondering where their field is headed

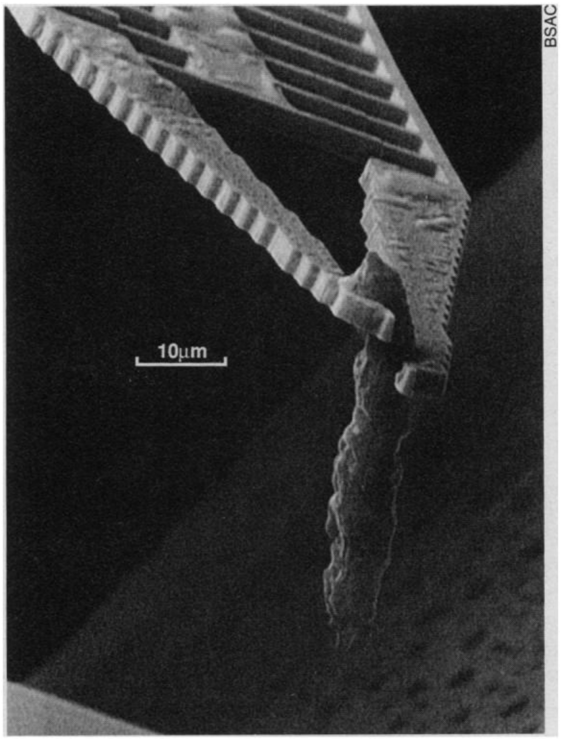
A CHORTLE ECHOED THROUGH A SPACIOUS San Francisco conference hall on 26 June when University of California, Berkeley, graduate student Chang-Jin Kim flashed a slide showing a pair of massive tweezers grasping a huge zucchini-shaped creature. The funny thing about the slide was that it was taken through a scanning electron microscope. Those "giant" tweezer arms spanning the 20-foot screen were actually bits of silicon about 400 microns long, smaller than your average flea. The "huge" creature clasped in the forceps was a one-celled protozoan.

What's the point of embracing a euglena? Kim noted late last month at the Transducers '91 conference (a gathering of microsensor and micromechanical device makers) that tweezers small enough to grasp a protozoan probably could serve well in a minuscule robotic hand. The mini-hand might, say, precisely position a cell under a microscope or simplify the fine handiwork of microsurgical operations. But for Kim and the 800 other technophiles who convened in San Francisco for the world's largest research show-and-tell devoted to the smallest human-made gizmos, just showing what their creations are capable of is enough; most of the researchers are a long way from tailoring their minuscule sensors and manipulators to any very specific use. So far, they have mostly been honing their microfabrication skills and scratching their heads about what place their wares ultimately might have in the world.

Not that the micromachinists have any doubts about the potential importance of their devices. By monitoring pressure, motion, light, magnetic fields, flow rates, and chemistry, tiny sensors could endow larger structures and machines, from vacuum cleaners to space craft, with artificial sensory physiology. Integrating these sensors with microelectronic circuitry on the same piece of silicon real estate could result in devices that are smart as well as sensitive, able to interpret as well as detect environmental cues. And if the system included miniature mechanisms, it could also react to its environment as well.

"The potential impact will exceed anything that has come along since microprocessors," electrical engineer Kensall D. Wise of the University of Michigan said at the meeting during a plenary talk. It might even exceed the impact of microprocessors, added Wise, who heads his university's Center for Integrated Sensors and Circuits. Richard S. Muller, a director of the Berkeley Sensors and Actuators Center (BSAC) and general chairman of the conference, cautions that raising unrealistic expectations in an embryonic endeavor can backfire. But the Japanese government needs no convincing. This year, it approved $160 million for a multiyear national effort in micromachine technology.

To date, only a few micromachined products have actually made it into large-scale commercial settings. The most prominent example is found under the hood of new cars. In the intake manifold is mounted a tiny pressure sensor incorporating a silicon membrane only several microns thick that flexes or relaxes with pressure changes. The membrane transduces that motion into electrical signals that feed into engine-control



BSAC

Slim pickings. *Microgripper nabs a euglena.*

circuitry. Other commercial micromachined products include silicon flow sensors for climate control in buildings and micronozzles for computer printers.

At least in the automotive sensor market, which has already grown to $1.5 billion by some estimates, obvious new niches are beckoning, says Robert Sulouff Jr. of Siemens Automotive. Microfabricated silicon-based sensors may soon be serving as accelerometers (motion sensors) in collision air bag systems, in suspension and braking systems that adapt to the condition of the road, and even in automated navigation and guidance controls. "The opportunity for several companies to have annual sales of $100 million with excellent growth prospects has attracted considerable interest," Sulouff noted.

Most micromachinists, though, aren't chasing entrepreneurial carrots yet. Many are pursuing pure research, using their tiny machines and sensors to probe microscopic phenomena. For example, Mark Tracey of Hatfield Polytechnic in Hatfield, England, and his colleagues plow tiny flow channels, 5 microns deep and 100 microns long, into silicon substrates in order to study how red blood cells deform as they travel through narrow conduits such as capillaries. Impairments in blood cell deformability play important roles in cardiovascular disease and in circulatory complications due to diabetes mellitus, Tracey noted.

Other micromavens are developing the techniques for making microfabricated sensors and actuators. Since the field originally budded from the microelectronics industry, most microsensor and actuator makers cleverly commandeer the same techniques and materials developed for making microprocessors—for the most part, microlithography on silicon.

In standard microlithography, engineers create tiny complex structures by shining ultraviolet light through precise stencils onto a silicon substrate that has been coated with polymers that weaken on exposure. The weakened regions are then washed away, exposing a pattern on the silicon that can serve as a base on which other materials can be deposited or formed. Alternatively, the pattern can be etched into the surface with acids. But these techniques are best suited to building or carving very thin structures, and so engineers have combined microlithography with a variety of deeper etching methods to create pits, trenches, channels, and membranes, and even complex, freely moving machine components such as meshed gear trains and microtweezers.

Extending the reach of their microscopic sculpting to new materials and structures is a key goal of the micromachinists. At the San Francisco meeting, engineers from MicroParts, a new company in Karlsruhe, Germany, and the University of Wisconsin, Madison, showed how to use intense x-rays from synchrotrons for creating thick (in this business that means several hundred microns) gears, hubs, and other components in metal rather than the usual silicon (see *Science*, 12 July, p. 143). In the process, known by its German acronym LIGA, the desired pattern is inscribed on a polymer layer with x-rays, which drill far deeper than the ultraviolet light of conventional microlithography. The weakened regions are then dissolved away, leaving behind a deep mold in which metals or other materials can be deposited. Dissolving away the remaining mold material leaves behind finished microparts, either attached to the substrate or free for subsequent assembly.

Although the LIGA process can yield thick metallic parts, presumably brawnier than the thinner silicon products of microlithography and etching, synchrotrons are scarce and expensive. And instead of yielding a complete, preassembled micromechanism, it produces separate parts, which must then be assembled. Still, MicroParts had representatives at the San Francisco meeting to tell researchers that it is open for LIGA orders. Also in late June, Georgia Tech electrical engineer Mark G. Allen and his colleagues reported that they had come up with an everyperson's alternative to LIGA, in which run-of-the-mill ultraviolet and visible radiation serve for carving deep micropart molds.

One of the most talked-about new microfabrication tools reported at the San Francisco meeting is a desk-top micromanufacturing system, which enables an engineer to design and fabricate tiny structures by tapping a few times on a computer keyboard and turning a knob or two. "This system can make three-dimensional structures including spheroids and pretty much anything else," Dan Ehrlich of the MIT-run Lincoln Laboratory in Lexington, Massachusetts, told his audience. Working at the video display of a computer-aided design (CAD) system, the operator first plots the exact shape and size of the desired microstructure. The computer translates that design into a pattern of cubic pixels 1 to 3 microns on a side. Starting at the surface of the material—generally silicon—and working downward layer by layer, a computer-aided manufacturing (CAM) laser chisels away the "volumetric pixels" at a rate of about 20,000 per second while the CAD/CAM system displays the micromachining operation.

Rather than vaporizing the silicon directly, the laser drives a process of chemical etching. It activates chlorine molecules near the silicon blank while locally heating the silicon. The chlorine then snatches silicon atoms from the blank's surface to form volatile silicon chloride molecules, which are swept out of the fabrication chamber. In one example, Ehrlich and his graduate student Ted M. Bloomstein machined what looks like the inside of a microscopic radar dish, 30 microns deep and 160 microns across, with a cone sprouting from the bottom. "The bowl took a couple of minutes to make," Ehrlich said. The researchers also can selectively deposit cobalt or platinum metal on the resulting structures by directing their laser to specific spots in the presence of metal vapors.

This ability could help electrical engineers build three-dimensional microcircuitry—another way to cram more computing capability into small spaces—or it could have some very different use. Like most of the micromachines and microsensors featured at the meeting, the metallized microstructures constitute answers to questions that have yet to be asked, says Hans Zappe of IBM Almaden Research Center in California. "Most important applications will be something no one at this conference can come up with now," he said. "Who would have thought that lasers would be reading bar codes in supermarkets?" ■ IVAN AMATO