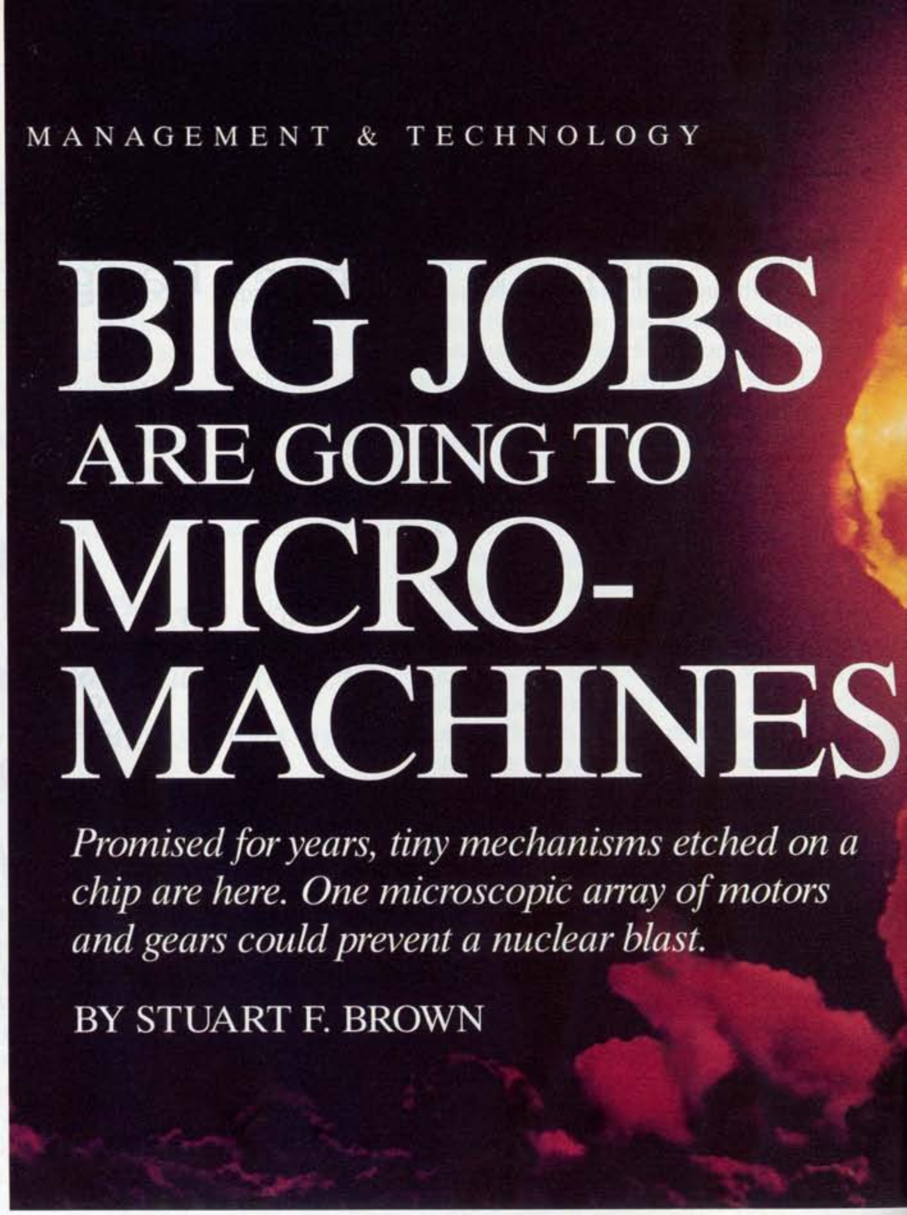
BIG JOBS ARE GOING TO MICRO-MACHINES

Promised for years, tiny mechanisms etched on a chip are here. One microscopic array of motors and gears could prevent a nuclear blast.

BY STUART F. BROWN



Unnoticed, like dust mites on a couch, are growing numbers of tiny mechanical gadgets with amazing capabilities. Rugged motion sensors smaller than a fingernail. Micromirrors, 1.2 million of the little devils crowded onto the area of a postage stamp, that pivot billions of times on hinges that never wear out. Electric motors with gears the size of a pollen grain that whir at an unprecedented 350,000 revolutions per minute. A museum of these devices would fit in a thimble.

They're taking over important jobs. The midget sensors trigger automotive airbags, and the micromirrors are used in projectors that beam an unusually bright, crisp image. Tiny motors, if their designers' hopes are realized, will prevent the accidental detonation of a city-destroying nuclear bomb. What these mechanisms have in common, aside from smallness, is that they are made using the same well-understood processes by which silicon and metals are built up like layers of a cake to form computer chips. They're produced with the same kind of photolithographic equipment, in clean rooms tended by the same breed of bunny-suited workers.

Except that this silicon moves. Computer chips, for all their data-handling prowess, are a visual bore. Computational miracles take place as electrons zoom through their millions of on-off switches. But even when viewed through a powerful microscope, there's no show for the eye to see. With the arrival of micromachines, more properly called micro–electromechanical systems, or MEMS, fanciers of mechanics and motion need gripe no longer about the nondrama of silicon. These chips, when magnified, resemble Erector Set creations.

Some 600 organizations worldwide are working on MEMS, according to consultant Roger Grace in San Francisco. About 150 are companies—half in the U.S.—pursuing commercial markets. Grace estimates the current global market for MEMS devices at $6 billion to $8 billion a year and believes the figure will reach $20 billion by 2002.

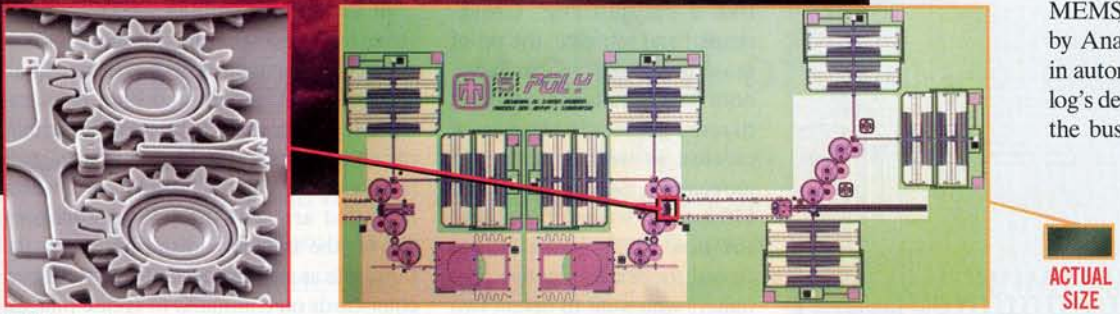
One slice of the business, small now in terms of commercial sales but likely to grow especially rapidly, is microfluidics devices, or bio-MEMS, used by pharmaceuticals researchers. Several dozen companies are developing chips that perform such tasks as blood analysis and the synthesis of new drug candidates. Bio-MEMS typically consist of a micromachined silicon laboratory on a chip with fluid passages, valves, and chambers for carrying out chemical reactions on a tiny scale.

More exciting to behold, however, are MEMS that are taking over essential mechanical chores outside the lab. Around the U.S., eclectic teams of scientists and engineers have developed marvels like these:

- At its fab in Cambridge, Mass., Analog Devices is cranking out, at the rate of a million a month, midget MEMS accelerometers that have slashed the cost of airbag controls. The company's accelerometer business, among the biggest of the recent MEMS innovations, has been growing 30% to 40% a year in dollars.
- Texas Instruments in Dallas has a chip facility devoted to producing its digital light processors, which are MEMS chips packed with all those micromirrors. TI sells the chips to 30 manufacturers, which have put them into more than 165,000 high-resolution projection systems.
- One of more than 60 MEMS startups in the U.S., Optical Micro-Machines in San Diego has figured out a better answer to the fiendishly delicate problem of switching fiber-optic signals. The MEMS devices it is developing will help telephone companies keep up with the explosion in Internet traffic.
- Should an airplane crash with a nuclear bomb on board, the weapon absolutely must not accidentally explode in a glowing mushroom cloud. Sandia National Laboratories in Albuquerque has come up with a prototype of a cheaper, space-saving MEMS mechanical safeguard.

Impressive as these devices are, developing them has taken longer than expected because of maddening difficulties arising in the production and operation of microscopic mechanisms. The origins of MEMS go back to 1955, when Bell Labs researcher Charles Smith published a paper discuss-

DEPARTMENT OF DEFENSE



Safety lock The small photos show gears the size of a pollen grain (left) that spin in the prototype "stronglink" (center) developed by Sandia Laboratories for a nuclear bomb. The dozens of components, "grown" fully assembled, all fit on a tiny chip.

ing the electrophysical properties of silicon. For one thing, its electrical resistance changes when it is flexed.

Exploiting this property in the 1960s, companies like Honeywell developed hydraulic-pressure sensors for aircraft flight-control systems that were more accurate than their predecessors. By the 1980s automakers and their suppliers began making similar sensors to monitor engine intake-manifold pressure in fuel-injected cars. Other early commercial MEMS applications included inkjet printer heads and small catheter devices for measuring blood pressure in surgical patients.

MEMS took a big leap beyond mere flexing and into oscillating and spinning parts when a sophisticated production technique called surface micromachining was introduced in 1985. Surface-micromachined MEMS can be made in any fab designed to produce CMOS (short for complementary metal-oxide semiconductor) memory or logic chips, the commonest variety. The happy news from a cost standpoint is that MEMS devices have feature sizes of one micron or greater, much larger than the 0.25-micron features on the latest Pentiums. Thus, MEMS don't have to be made with the newest and most expensive equipment. And after much struggle, process refinements have greatly raised the yield of devices that pass inspection.

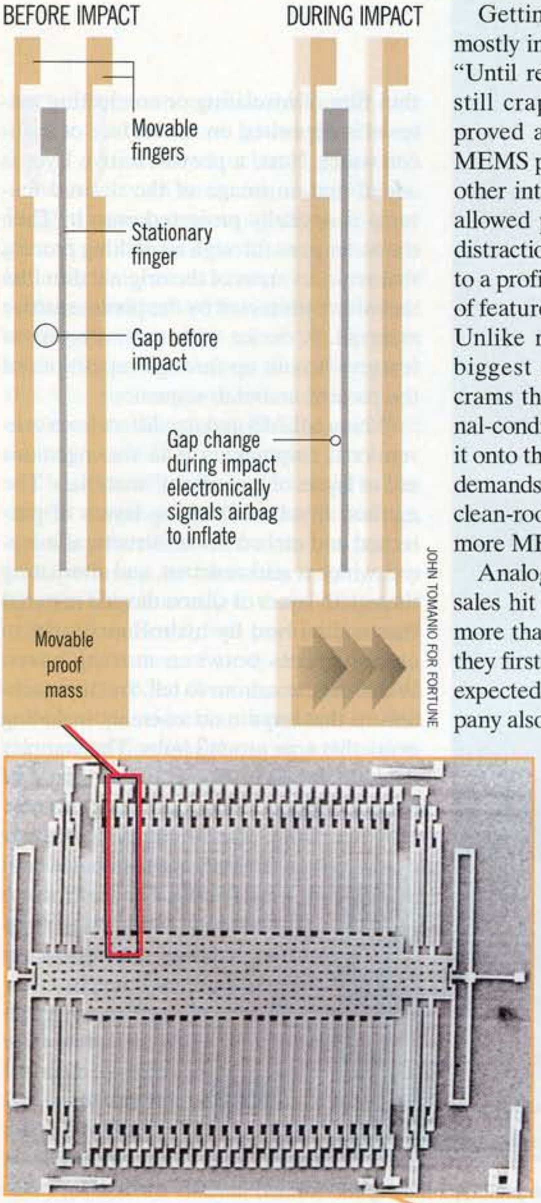
Like other CMOS products, MEMS are produced in a clean room through multiple pattern-and-etch sequences. First, a thin film of insulating or conducting material is deposited on the surface of a silicon wafer. Next, a photosensitive layer is added and an image of the desired features is optically projected onto it. Then the wafer goes through an etching process that removes areas of the original thin film that aren't protected by the photosensitive material. A device with several layers of features is built up through repetitions of the pattern-and-etch sequence.

Where MEMS making differs from conventional chipmaking is in the ingenious use of layers of "sacrificial" materials. The method involves stacking layers of patterned and etched silicon structural material, which is acid-resistant, and alternating them with layers of silicon dioxide material that is dissolved by hydrofluoric acid to create spaces between moving parts. What's left, wondrous to tell, are tiny mechanisms that require no assembly, including gears that spin around hubs. The complex devices shown on these pages, some of them five layers thick, were made this way.

One example is the tiny MEMS accelerometer built by Analog Devices for use in automotive airbags. Analog's design, the top seller in the business, uses an intricate movable silicon structure called a proof mass, which has spindly fingers protruding from each side, making it look like a stylized fish skeleton. Interleaved with its fingers, but not touching them, are stationary fingers. Together, the sets of fingers form a differential capacitor that can electrically sense changes in the gap between them.

When the car in which the airbag is installed is jolted, the proof mass jiggles slightly on spring mounts that look like hairpins. The resulting change in the gaps between the stationary and moving fingers creates a signal varying in proportion to the g force of the jolt. Bumping a curb, say, produces a minor jiggle that the accelerometer disregards. But if the capacitor senses enough force—roughly equal to hitting a wall at 14 miles per hour—the accelerometer tells the airbag to blow.

Analog had an eye on the potentially



JOHN TOMANIO FOR FORTUNE

Airbag sensor **The interleaved silicon fingers in the above photo of an Analog Devices accelerometer sense the jolt of a car crash and signal the airbag to inflate.**

huge automotive airbag market when it began working on MEMS accelerometers as a secret internal project in the late 1980s. At that time, recalls Chairman Ray Stata, automakers were relying for crash-severity sensing on mechanical devices that used a metal ball or cylinder in a tube. For reliable control, a car needed as many as five of the devices, each about the size of a stubby lipstick container and costing about $17. Stata says Analog is shipping its fingernail-sized accelerometers for less than $3 apiece, while meeting the tough requirements of quality programs like Six Sigma and QS9000.

Getting there took a relentless effort, mostly in refining the fabrication process. "Until relatively recently, our yields were still crappy," Stata confides. They improved after 1996, when Analog moved MEMS production out of a plant at which other integrated circuits were made. This allowed process experts to focus without distraction on driving the MEMS yield up to a profitable level. Because of the variety of features on the chips, it was a challenge. Unlike rival accelerometer makers, the biggest of which is Motorola, Analog crams the mechanical device and the signal-conditioning circuits that go along with it onto the same chip. It's an approach that demands exceptional mastery of a 430-step clean-room process, but pays off by nesting more MEMS on each silicon wafer.

Analog, a publicly held company whose sales hit $1.2 billion in 1998, has shipped more than 17 million accelerometers since they first hit the market in 1993. Volume is expected to keep growing rapidly. The company also sees a big future for accelerometers that sense gentler motion. Its latest model is an elegant creation called the ADXL202, which when magnified looks like a Persian rug. Cross-shaped and intricate, the proof mass at its center can move both north-south and east-west to sense g forces in two axes of motion as well as diagonal movement. Selling for about $10 each in volume quantities, the new MEMS chip is designed for nonautomotive customers who want to detect two g's or less, compared with the 50 g's an airbag sensor can measure.

Microsoft's hand-held Sidewinder Freestyle Pro computer-game controller replaces push buttons with the ADXL202, which senses the player's body motion. When the player leans to the right, the view from his fighter plane's cockpit is realistically banked. The two-axis device is also used in a product called Back Talk, made by Bio Kinetics Corp. of San Antonio. Designed to reduce the risk of workplace back injuries, the pager-sized gadget clips on the user's belt and issues an audio or vibrating alarm when he or she makes an ergonomically unsound move, such as lifting from the waist instead of from the knees. Even bigger markets could develop for the next-generation product Analog Devices is preparing to introduce: a MEMS whose pairs of interleaved fingers provide the same kind of navigational information as a spinning gyroscope.

Texas Instruments launched its first commercial digital-light processors (DLPs) in 1996, after researchers had spent nine years learning how to pack a whole lot of moving parts onto a chip. The optical MEMS device now comes in versions containing 0.5 million, 0.75 million, or 1.2 million tiny mirrors, depending on how much resolution the customer wants.

DLPs form the heart of a variety of bright, sharp projection systems selling for $4,500 to $120,000. They include home theaters that project TV programs onto large screens, portable computer-driven projectors for conference-room presentations, and more powerful projectors for concert halls and stadiums. A prototype of a DLP cinema projector, built by Digital Projection Ltd. of Atlanta, was recently demonstrated, which raises the prospect of commercial theaters' switching from fragile, expensive film prints to movies delivered in electronic form.

In TI's system, light focused by a lens is shone through a spinning transparent wheel to break it down into a stream of rapidly alternating red, green, and blue primary-color segments that are beamed at the mirror chip. Responding to electronic signals from a laptop PC, a CD-ROM, or a videotape that are sent through a processing board, the mirrors on the chip play the same role as stadium spectators who display color cards on command to create images.

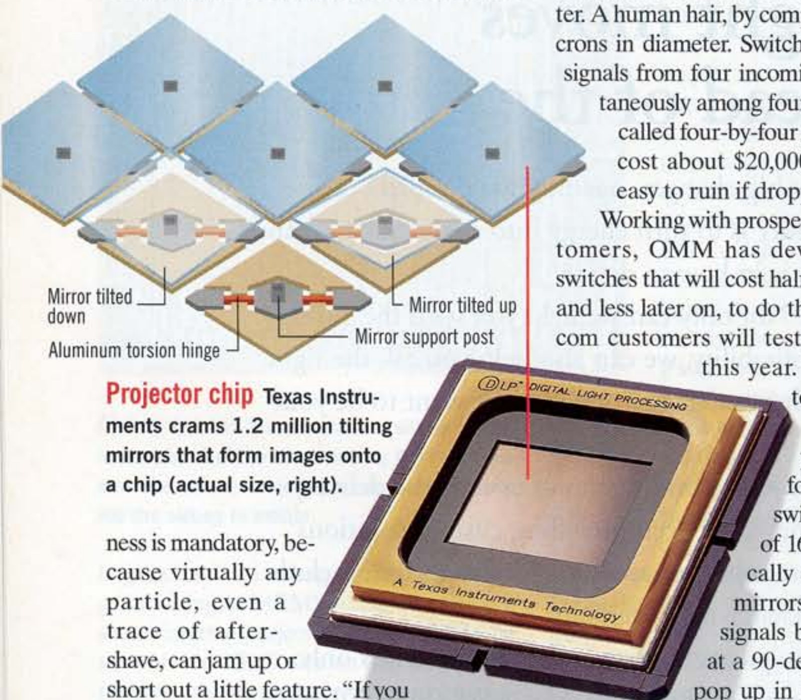
The mirrors form pictures by flipping into or out of each color's light path at the correct instant. Electrostatic attraction tilts the mirrors as many as 10,000 times per second. By popping up to supply the correct color, the mirrors behave like reflecting pixels to form a much brighter and crisper image, with truer colors, than is possible with conventional equipment. Brightness gradations within a frame are achieved by varying the on-time of the individual mirrors. The image the DLP creates is projected through a second lens onto a viewing screen.

Who could have thought up such an audacious thing? It was physicist Larry Hornbeck, working at TI's Central Research Laboratories, who invented the DLP in 1987. Last year it won him an Emmy award for outstanding engineering development from the Academy of Television Arts and Sciences.

TI tried several generations of mirror architecture on the way to the current ultra-reliable design, which is manufactured in a six-layer pattern-and-etch process using proprietary aluminum alloys instead of silicon, with organic-resin sacrificial layers in between. The mirrors pivot on a pair of aluminum torsion beams, a type of twisting hinge. One might expect that the aluminum would eventually break. Not so.

As it turns out, the behavior of thin-film metal is quite different from the much thicker metal structures we live with in the big world. Quality and reliability engineer Michael Douglass has run digital-mirror devices in nonstop tests for 1.7 trillion on-off cycles so far—the equivalent of about 100 years of service in a projector—with no sign of fatigue or cracking. "We still haven't had time to find out what the ultimate life is," Douglass says.

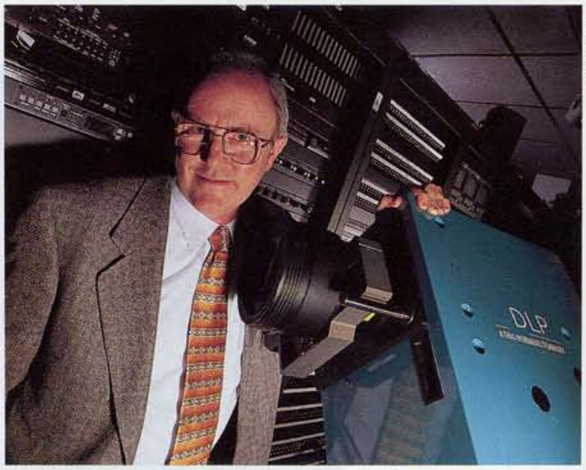
JOHN TOMANIO FOR FORTUNE



Projector chip Texas Instruments crams 1.2 million tilting mirrors that form images onto a chip (actual size, right).

Though TI's MEMS fab is equipped with standard semiconductor process equipment, special steps have to be taken to ensure profitable yields. Most customers insist on devices with 100%-perfect mirrors, though a few will accept a maximum of three duds on an array. Relentless attention to cleanliness is mandatory, because virtually any particle, even a trace of aftershave, can jam up or short out a little feature. "If you can smell it, it will kill a mirror," says Michael Mignardi, TI's product manager for digital-mirror devices. Packaging is a big deal because MEMS perish if their fragile surfaces come in contact with the outside world. After wafers of TI's devices are tested and then diced into individual chips, the good ones are sealed in glass-windowed housings. Finally, the housings are filled with dry nitrogen gas; little mirrors abhor humidity.

MEMS populated with mirrors may be destined for an even more important role. San Diego's Optical Micro-Machines is a 14-employee startup founded in 1997 with backing from prominent venture capital firms, including Sevin Rosen Venture Partners. The company has a sharply focused mission: Develop reliable and affordable optical switches to help the expansion of fiber-optic telecommunications systems.



BRIAN COATS

Physicist Larry Hornbeck thought up TI's projection system.

The so-called "bulk optics" mechanical switches currently used by the telecom industry have a lot of shortcomings. Using what looks like a speedometer needle, they move a fiber strand along an arc, coming to rest where it aligns with one of several other strands. The mechanical switches require fancy motors, ultrahigh-precision bearings, and intricate hand assembly to align the fibers, which are only nine microns in diameter. A human hair, by comparison, is 100 microns in diameter. Switches that can shunt signals from four incoming strands simultaneously among four outgoing ones—called four-by-four matrix switches—cost about $20,000 each. They are easy to ruin if dropped.

Working with prospective telecom customers, OMM has developed MEMS switches that will cost half as much initially, and less later on, to do the same job. Telecom customers will test prototypes later this year. The first model to go into volume production will probably be a four-by-four matrix switch with an array of 16 tiny electrostatically actuated pop-up mirrors that can reroute signals bounced off them at a 90-degree angle. They pop up in different patterns to shunt four incoming signals as desired. Even when ganged together to make a 16-by-16 switch, a quartet of the MEMS switches along with their circuitry measures only five inches on a side. A comparable 16-by-16 bulk-optic switch is as big as a window air conditioner. The market for optical switches that OMM hopes to break into is projected to grow to $1.5 billion a year by 2003.

One of the dream playgrounds for MEMS researchers is at Sandia, the huge Department of Energy lab that conducts weapons-related research and various cooperative programs with industry. Sandia boasts a first-rate fab built to produce chips that can stand up to radiation in outer space and the pulse of electromagnetic energy that accompanies a nuclear blast. The lab's MEMS program has a staff of 500 and a $100 million annual budget.

A tiny Sandia creation built last year, which captivates all who see a videotape of it running, is a prototype MEMS "stronglink," a safety lockout device designed to prevent a nuclear weapon from going off accidentally. That's a real worry for the bomb stewards; airplanes with nukes aboard have crashed, and a Titan II missile silo in Damascus, Ark., blew up in 1980, spitting warheads into the countryside. The unthinkable didn't happen because the bombs had well-designed mechanical stronglinks.

The ones currently in use are an elaborate mechanism reminiscent of the Ultra encoding machine used by the Germans in World War II. It has 450 clockwork parts, laboriously machined from stainless steel at a cost of about $25,000. "This is what stands between you and a blinding white flash," says Paul McWhorter, Sandia's deputy director for microsystems science, handing a visitor one of the baseball-sized gadgets. "The question is, Can we achieve this same function, with higher degrees of safety and reliability, and build the entire system on a chip for a dollar? That's our motivation for working in MEMS." Sandia is sharing its experience from developing a cheaper stronglink with industry, which it hopes will refine the manufacturing know-how. Says McWhorter: "The designers tell us they are never going to put these into a weapon until they see them in cars."

The brainchild of Steve Rodgers, a Sandia technician who tinkers with model rockets and airplanes in his spare time, Sandia's MEMS stronglink can best be described as Rube Goldberg meets Gordon Moore. Peering through a microscope, you can see the device's prime movers, seven unorthodox electric motors called comb drives. Consisting of paired comblike silicon structures with their teeth intermeshed, the drives perform reciprocating motion when a fluctuating voltage applied to them creates an electrostatic field. A connecting rod joins each comb drive to an eccentric gear, which converts the reciprocating motion to rotary motion. Then a train of reduction gears slows the rotary motion while multiplying its torque, or power, to a useful level. Finally, a rack-and-pinion gear converts this to linear motion.

The stronglink is designed to cooperate only when someone enters a 24-number sequence correctly, leaving just a one-in-16 million chance of defeating it by entering random numbers. Each time a correct number is entered, motors switch on and steer a pin through the correct turns in a slotted maze. If a wrong number is entered, the pin enters a dead-end path in the maze, and the device locks up permanently. But when all 24 digits are entered correctly, the pin negotiates the entire maze, and the rack and pinion—which has a pair of gears at its tip—meshes with another incomplete gear train. Now the second gear train can drive a second rack and pinion, which raises a folded mirror. And the mirror intersects a beam of light, directing it to an optical sensor that arms the bomb. Simple, no?

Sandia has done all sorts of inquiries into the fundamental properties and durability of micromechanisms. At first, its micromotors would fail from rubbing wear after only 100 revolutions. Now, by adding little friction-reducing dimples to the undersides of gears, coating parts with atomic whiskers that act as an artificial lubricant, and massaging the electrical drive signals to eliminate jerkiness, researchers have kept one comb drive running for 190 days, which is ample durability for a stronglink that needs to be used just once.

In tiny shapes, as Sandia is learning, silicon behaves in fascinating ways. "It turns out to be the ultimate mechanical material," says McWhorter. "You can flex it billions of times without seeing any signs of mechanical fatigue; it just isn't an issue at these small scales. And you don't worry anymore about what something weighs or its inertia. Imagine driving your car 600 miles an hour and throwing it into reverse without damaging it."

A Texan who drives a sand-colored Hummer, McWhorter is an energetic but not glassy-eyed MEMS proselytizer who likes cool demonstrations. He has a MEMS comb-drive motor linked to an eccentric gear and wired up to electrical leads under a microscope. On the wall is a video monitor and on the table a computer-gaming joystick. When a visitor pushes the joystick forward, the micromotor on the screen revs up to 350,000 rpm in an instant, making it the fastest electric motor ever built. It stops or reverses just as quickly. The gear, the size of a pollen grain, has teeth the size of red blood cells. Amazing is the only word for it.

To spread its MEMS expertise as rapidly as possible, Sandia offers a three-day micromachine-design course, which has been attended over the past year and a half by about 500 people from industry, academia, and the military. Part of what attendees get for their $10,000 fee is functioning samples of their MEMS ideas, which are sent through the fab. Not long ago, a FORTUNE 500 company booked an entire class so that its people could attend without sharing their ideas with strangers.

A special breed of person is needed to design MEMS, which straddles the domains of mechanical and electrical engineering. One incubator for MEMS specialists is the University of California's Berkeley Sensor and Actuator Center, where a faculty of seven works with 85 graduate students on a wide range of projects. Started in 1986 with funding from the National Science Foundation, the center has its own fab equipment. A roster of 25 big-name industrial and institutional members chip in $6 million a year in exchange for a voice in research agendas and early access to the results.

Many of the graduate students and postdoctoral researchers have their real-world jobs lined up well before they leave the nest. Among them is Lilac Muller, 26, who's working on putting a polysilicon MEMS actuator on the tip of a computer disk-drive read-write arm to improve its positioning accuracy. With a wrist added to the arm, she says, the read-write mechanism can lay down more tightly spaced tracks of data than was previously possible, greatly increasing storage capacity.

The ultimate MEMS disk drive, Muller says, would have the arm, a microgimbal and "picoslider" for positioning the head, and the associated electronics all fabricated on one structure to eliminate a lot of the assembly costs in today's disk drives. Other researchers are working on even denser MEMS-actuated memories. IBM's Zurich lab is perfecting a nonmagnetic system that uses 1,024 styluses in an array measuring just three millimeters square to melt minute holes, representing bits of data, on the surface of a plastic-coated disk. The information is erased by heating the disk to remelt the plastic.

STEVE LABADESSA

Optical switch A San Diego startup, Optical Micro-Machines, uses tiny mirrors to shunt optical signals.

Projects in the MEMS field often receive funding from the Defense Advanced Research Projects Agency. DARPA launched a MEMS program in the early 1990s to push along applications that are on the military's wish list but that the commercial world hasn't yet decided to invest in. Hot items on DARPA's funding list include an inertial-navigation chip, which could cheaply track the location of equipment, and radio-frequency MEMS, which could shrink the size of radios.

"We're on the verge of the second silicon revolution," reflects Sandia's McWhorter. "The first one has made transistors smaller and smaller for 30 years. The second one is creating a whole new generation of integrated circuits that not only think but can sense and act as well." When silicon can move, the possibilities can only be guessed at. ■