THE TECHNOLOGY REVIEW TEN

What if you had a crystal ball that foretold the future of technology? Imagine, for example, if you had known in 1990 just how big the Internet was going to be 10 years hence. Sorry, that crystal ball doesn't exist. But in this special issue of *Technology Review*, we offer you the next best thing: the educated predictions of our editors (made in consultation with some of technology's top experts). We have chosen 10 emerging areas of technology that will soon have a profound impact on the economy and on how we live and work. These advances span information technology, biotechnology and nanotechnology—the core of *TR* coverage in every issue. All of these areas merit special attention in the decade to come. In each area we've chosen to highlight one innovator who exemplifies the potential and promise of the field. Keep this issue around and see how well our predictions hold up—even without the aid of that crystal ball.

—*The Editors*

Duke University's Miguel Nicolelis handles a robotic arm. Brain signals from an owl monkey (seen on the monitors to the right) control the arm's movement.

MIGUEL NICOLELIS

Brain-Machine Interfaces

Belle, a nocturnal owl monkey small enough to fit comfortably in a coat pocket, blinks her outsized eyes as a technician plugs four connectors into sockets installed in the top of her skull. In the next room, measurements of the electrical signals from some 90 neurons in Belle's brain pulse across a computer screen. Recorded from four separate areas of Belle's cerebral cortex, the signals provide a window into what her brain is doing as she reaches to touch one of four assigned buttons to earn her reward—a few drops of apple juice. Miguel Nicolelis, a Duke University neurobiologist who is pioneering the use of neural implants to study the brain, points proudly to the captured data on the computer monitor and says: "This readout is one of a kind in the world."

The same might be said of Nicolelis, who is a leader in a competitive and highly significant field. Only about a half-dozen teams around the world are pursuing the same goals: gaining a better understanding of how the mind works and then using that knowledge to build implant systems that would make brain control of computers and other machines possible. Nicolelis terms such systems "hybrid brain-machine interfaces" or HBMIs. Recently, working with the Laboratory for Human and Machine Haptics at MIT, he scored an important first on the HBMI front, sending signals from individual neurons in Belle's brain to a robot, which used the data to mimic the monkey's arm movements in real time.

In the long run, Nicolelis predicts that HBMIs will allow human brains to control artificial devices designed to restore lost sensory and motor functions. Paralysis sufferers, for example, might gain control over a motorized wheelchair or a prosthetic arm—perhaps even regain control over their own limbs. "Imagine," says Nicolelis, "if someone could do for the brain what the pacemaker did for the heart." And, in much the same way that a musician grows to feel that her instrument is a part of her own body, Nicolelis believes the brain will prove capable of readily assimilating human-made devices.

Ongoing experiments in other labs are showing that this idea is credible. At Emory University, neurologist Phillip Kennedy has helped severely paralyzed people communicate via a brain implant that allows them to move a cursor on a computer screen *(see "Mind Over Muscles,"* TR *March/April 2000)*. And implants may also shed light on some of the brain's unresolved mysteries. Nicolelis and other neuroscientists still know relatively little about how the electrical and chemical signals emitted by the brain's millions of neurons let us perceive color and smell, or give rise to the precise movements of Brazilian soccer players—whose photos adorn the walls of the São Paolo native's office. "We don't have a finished model of how the brain works," says Nicolelis. "All we have are first impressions."

Others in Brain-Machine Interfaces

Organization	Project
Andy Schwartz (Arizona State University)	Neural control of robotic arm
John Donoghue (Brown University)	Brain representation of movement
Richard Andersen (Caltech)	Improved neuroelectrode systems
Phillip Kennedy, Roy Bakay (Emory University)	Communication systems for paralyzed patients

Nicolelis' latest experiments, however, show that by tapping into multiple neurons in different parts of the brain, it is possible to glean enough information to get a general idea of what the brain is up to. In Belle's case, it's enough information to detect the monkey's intention of making a specific movement a few tenths of a second before it actually happens. And it was Nicolelis' team's success at reliably measuring tens of neurons simultaneously over many months—previously a key technological barrier—that enabled the remarkable demonstration with the robot arm.

Still, numerous stumbling blocks remain to be overcome before human brains can interface reliably and comfortably with artificial devices, making mind-controlled prosthetic limbs or computers more than just lab curiosities. Among the key challenges is developing electrode devices and surgical methods that will allow safe, long-term recording of neuronal activities. Nicolelis says he's begun working with Duke's biomedical engineering department to develop a telemetry

Photograph by PATRICIA MCDONOUGH

chip that would collect and transmit data through the skull, without unwieldy sockets and cables. And this year Nicolelis will become co-director of Duke's new Center of Neuroengineering and Neurocomputation, which will explore new combinations of computer science, chip design and neuroscience. Nicolelis sees the effort as part of an impending revolution that could eventually make HBMIs as commonplace as Palm Pilots and spawn a whole new industry—centered around the brain.

—Antonio Regalado

CHERIE KAGAN

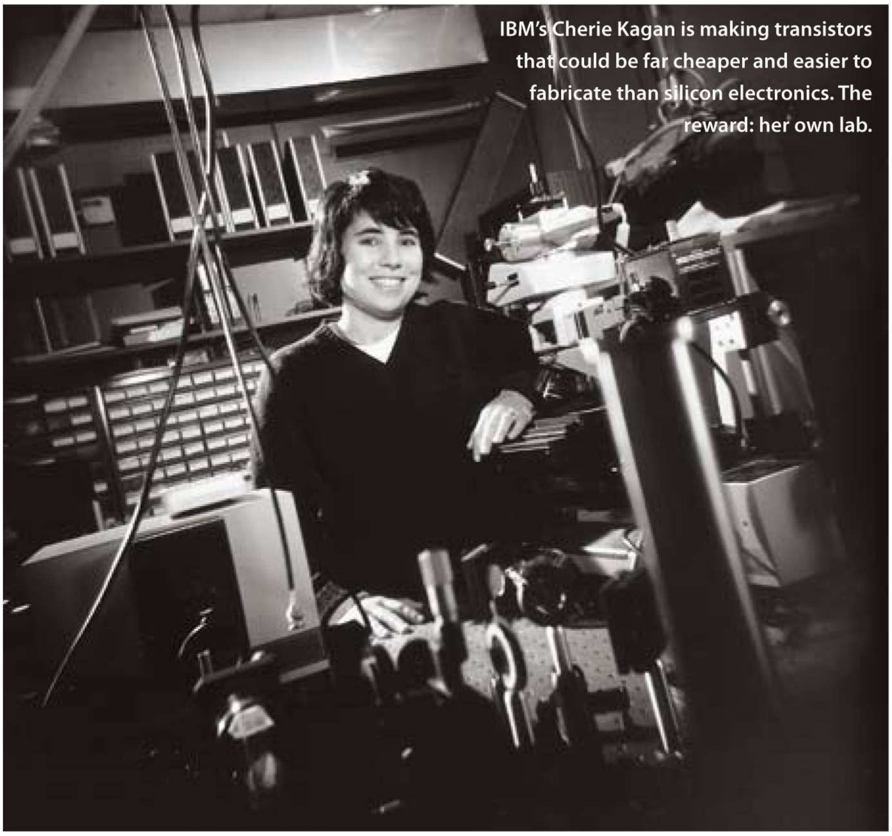
Flexible Transistors

The implementation of pervasive computing—the spread of digital information throughout society—will require electronics capable of bringing information technology off the desktop and out into the world *(see "Computing Goes Everywhere," p. 52)*. To digitize newspapers, product labels and clothing, integrated circuits must be cheap and flexible—a tough combination for today's silicon technology. Even the cheapest form of silicon electronics—the cut-rate "amorphous" silicon used to drive laptop display screens—is too pricey. What's more, it's difficult to incorporate silicon electronics on bendable surfaces such as plastics.

Technology innovators are taking a couple of routes around these limits. Some researchers are trying to reinvent amorphous silicon. Others have abandoned inorganic compounds like silicon to develop transistors based on organic (carbon-based) molecules or polymers. These organic electronics are inexpensive to manufacture and compatible with plastic substrates. Indeed, research teams at places such as Lucent Technologies' Bell Labs, England's University of Cambridge and Pennsylvania State University have made impressive progress, and commercial products are nearing the market. Last fall, for example, Philips Research in Eindhoven, the Netherlands, showed off the first prototype of a rudimentary display driven by polymer semiconductors. But there's a catch: Organics are far slower than their silicon cousins.

Others in Flexible Transistors

Organization	Project
Lucent/Bell Labs (Murray Hill, NJ)	Organic circuits
Richard Friend (University of Cambridge)	Organic light-emitting diodes
Joseph Jacobson (MIT)	Printed inorganics
Thomas Jackson (Penn State)	Organic transistors



IBM's Cherie Kagan is making transistors that could be far cheaper and easier to fabricate than silicon electronics. The reward: her own lab.

Now, a 31-year-old materials scientist at IBM, Cherie Kagan, may have opened the door to cheap, flexible electronics that pack the mojo needed to bring ubiquitous computing closer. Her breakthrough? A compromise: transistors made from materials that combine the charge-shuttling power and speed of inorganics with the affordability and flexibility of organics.

These hybrids were created by chemist David Mitzi at IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y. By the time Kagan arrived at Watson in 1998 following a stint at Bell Labs (she earned a PhD from MIT in 1996), Mitzi had already shown that his materials possessed intriguing electronic properties. Kagan had a hunch they might make good transistors. But she needed quick results; she'd been hired as a postdoc—a limited-time offer.

At the outset, the transistors flipped on and off sluggishly. "The first times, I didn't want to calculate [the speed]," says Kagan. But she kept tweaking, and in less than a year she had increased the mobility of electric charges through her transistors by four orders of magnitude—matching the speed of amorphous silicon and far exceeding most organic transistors. The results won her a staff position and her own lab at IBM.

Kagan has since increased the speed by another 50 percent; further fine-tuning, she believes, could provide at least another doubling in acceleration. Not only may the hybrids be far faster than amorphous silicon, they have a key advantage over silicon-based electronics. Like some organic materials used to make transistors, the hybrid materials can be dissolved and printed onto paper or plastic just like particles of ink. "I make my materials in a different lab and carry them over and add some liquid and spin them on," says Kagan. "It's not very sophisticated, which is sort of the goal, right? You really want it to be cheap."

Thomas Jackson, a transistor expert at Penn State who is developing organic circuits, says Kagan's "fledgling results" could pave the way for fast yet flexible electronics. Jackson credits Kagan with seizing the opportunity. "Not only does she have her own pocket of competence,

Photograph by LARRY BUSACCA

but she's able to look around and see exciting possibilities and then bring things together. IBM has been working on these sorts of materials for some time, but it took the energy and enthusiasm and vision and perspective of Cherie to translate that into a thin-film transistor."

The transistors could compete with organic electronics in a variety of applications, such as radio-frequency product ID tags. And then there's the $20 billion-per-year market for flat-panel video displays, where the speed of Kagan's transistors could really make a difference. Quicker circuits would deliver sharper displays than those driven by amorphous silicon at a fraction of the cost. That would open the door to affordable wall-sized displays or high-quality displays that pop out of your pen. If all goes well, the materials could be used in cheap, flexible displays within five years.

Of course, bright displays that fit in your pocket will require portable power, and that has Kagan pondering her next research challenge: cheap, flexible materials for solar cells to liberate pervasive computing from bulky batteries. "You aren't going to want to carry a battery around with your lightweight flexible display," she says. —*Peter Fairley*

USAMA FAYYAD

Data Mining

"Hello again, Sidney P. Manyclicks. We have recommendations for you. Customers who bought this title also bought..."

Intrusive? A touch of personal attention in the sterile world of e-shopping? Both, perhaps—but definitely a tour de force of database technology. Conventional databases sort though a few megabytes of structured data to find answers to specific queries. But compiling a simple recommendation list requires a system that can burrow through gigabytes of Web site visitor logs in search of patterns no one can anticipate in advance.

Welcome to data mining, also known as knowledge discovery in databases (KDD): the rapidly emerging technology that lies behind the personalized Web and much else besides. The emphasis here is on "emerging," says Usama Fayyad, who should know: data mining didn't exist as a field until he helped pioneer it.

In 1987, the Tunisian-born computer scientist was a graduate student at the University of Michigan. He had taken a summer job with General Motors, which was compiling a huge database on car repairs. The idea, he says, was to enable any GM service technician to ask the database a question based on the model of car, the engine capacity, and so on, and get a quick, appropriate response. Sounds straightforward. But, recalls Fayyad, "there were hundreds of millions of records—no human being could go through it all." The pattern recognition algorithm he devised to solve that problem became his 1991 doctoral dissertation, which is still among the most cited publications in the data-mining field.

Others in Data Mining

Organization	Project
Howard Wactlar (Carnegie Mellon)	Search very large video collections
Marti Hearst (University of California, Berkeley)	Automated discovery of new information from large text collections
Nokia Research Center (Helsinki, Finland)	Finding recurrent episodes in event sequence data
Raghu Ramakrishnan (University of Wisconsin)	Visual exploration of data on the Web

Data mining proved to have surprisingly broad application. Fayyad left Michigan for NASA's Jet Propulsion Laboratory, where he applied his techniques to astronomical research. In particular, his algo-

DigiMine's Usama Fayyad devises algorithms that detect meaningful patterns in massive collections of information.

Photograph by KAREN MOSKOWITZ

rithm helped in automatically determining which of some two billion observed celestial objects were stars and which were galaxies. The tool also helped find volcanoes on Venus from the huge number of radar images being transmitted from space probes. A geologist could retrieve the image of a previously identified volcano; the computer would then examine the picture for patterns and search through other images for similar patterns. That worked so well, Fayyad says, that "pretty soon the military intelligence people were all over us, wanting to use it. And so were doctors, who wanted to do automatic searches of radiology images." In 1995, in response to this widening interest, Fayyad and his colleagues planned a full-scale international conference on KDD. The conference drew about 500 participants, more than double what had been expected. (KDD 2000 drew 950.)

By this time, with the Internet gushing information onto everyone's desktop, the urgency for data mining was becoming evident in the corporate world. IBM and other industry giants sensed a market—and wanted in. Microsoft set its sights on Fayyad and enticed him to join the company's research labs. "They suggested that I take a look at databases in the corporate world," says Fayyad. "It was pretty sad. In many companies, the 'data warehouses' were actually 'data tombs': the data went in and were never looked at again." Fayyad joined Microsoft in 1996 and organized a new research group in data mining. "We looked at new algorithms for scaling up to very large databases—gigabytes or larger," he says.

By decade's end, Fayyad had caught the entrepreneurial bug sweeping through computer science labs. "I realized that even the organizations that loved the idea of data mining were having trouble just maintaining their data." What they needed, he reasoned, was a company to host their databases for them, and provide data-mining services on top of that. The result was digiMine, a Kirkland, Wash., startup that opened for business in March 2000 with Fayyad as CEO.

And the future of data-mining technology? Wide open, says Fayyad—especially as researchers begin to move beyond the field's original focus on highly structured, relational databases. One very hot area is "text data mining": extracting unexpected relationships from huge collections of free-form text documents. The results are still preliminary, as various labs experiment with natural-language processing, statistical word counts and other techniques. But the University of California at Berkeley's LINDI system, to take one example, has already been used to help geneticists search the biomedical literature and produce plausible hypotheses for the function of newly discovered genes.

Another hot area, says Fayyad, is "video mining": using a combination of speech recognition, image understanding and natural-language processing techniques to open up the world's vast video archives to efficient computer searching. For instance, when Carnegie Mellon University's Informedia II system is given an archive of, say, CNN news clips, it produces a computer-searchable index by automatically dividing each clip into individual scenes accompanied by transcripts and headlines.

Fayyad hopes that ultimately the techniques of data mining will become so successful and so thoroughly integrated into standard database systems that they will no longer be thought of as exotic. "People will just assume that their database software will do what they need."

—M. Mitchell Waldrop

RANJIT SINGH

Digital Rights Management

ContentGuard's Ranjit Singh manages access to online digital property.

Sitting in his office in McLean, Va., Ranjit Singh is at ground zero of what may be the biggest—and bloodiest—of the many battles that will shape the Internet during the 21st century's initial decade. The battle lines are sharply drawn. On one side are owners of intellectual property, or content: books, music, video, photographic images and more. On the other are Internet users—think Napster—who want content to be freely distributed.

And then there is Singh, president of ContentGuard, a company that spun out of research at Xerox's Palo Alto Research Center (PARC) on a mission to commercialize content protection in a wired world. "The Internet changes everything," says Singh, 48, an England-born technology manager whose resume glitters with senior positions at Xerox, Citibank and Digital Equipment plus a number of startups. "The Internet," Singh continues, "allows perfect reproduction of digital content and totally frictionless distribution." A few mouse clicks send a work to millions of users, but the creators and owners of the content won't necessarily collect dime one *(see "Your Work Is Mine!"* TR *November/December 2000).*

Ouch! You can bet the pain felt by content owners who see their stuff flying everywhere via the Net will translate into action. Which is what Singh and ContentGuard are about. Digital rights management, or DRM, is "the catalyst for a revolution in e-content," says Singh. "DRM will allow content owners to get much wider and deeper distribution than

Photograph by CHRIS HARTLOVE

be able to buy the content they want "without needing special viewers or downloads and without putting the user through hoops," he argues. To resolve that, ContentGuard has forged multiple partnerships with digital standard-bearers such as Microsoft and Adobe Systems, and has extended its technology so that it applies across many media, including books, music and video.

Captivating as the possibilities of DRM are, it is still in its early days. Says John Schwarz, CEO of Reciprocal, Inc., a distributor of ContentGuard and other DRM solutions: "We are probably a year or so away from seeing broad adoption of DRM by the marketplace."

Some analysts are more skeptical:

Others in Digital Rights

Organization	Project
InterTrust Technologies (Santa Clara, Calif.)	Develops peer-to-peer distributed DRM technology
Reciprocal (New York)	DRM clearinghouse
Digimarc (Tualatin, Ore.)	Watermarking to embed an imperceptible code
Alchemedia (San Francisco)	"Clever Content" platform safeguards digital content

"I'm not convinced content can be protected in the Internet era," says Eric Scheirer, who tracks DRM issues for Forrester Research. "People want flexible access to content." Proof is Napster, of course, which represents a phenomenon Scheirer calls "unstoppable." Even if Napster is put out of business by the courts, he predicts that the frictionless distribution of digital content among the millions of Internet users will live on.

But Singh is betting heavily that DRM will prevail and, ironically, he thanks Napster. "Napster turned this whole issue into a CEO-level question. The very highest corporate officers now are looking into content management issues, and they want to protect their property."

That, says Singh, augurs wider use of DRM. "Here's the virtual cycle you will see: The more content a business puts online, the faster it will want to put still more content up, because it will see the economic benefits and users will see the benefits of gaining access to more content. That's why we are seeing an explosion here." —*Robert McGarvey*

ever before," he maintains. "You can see who is passing your content to whom."

Stripped to its essence, DRM—as provided by ContentGuard and a number of competitors—amounts to an encryption scheme with a built-in e-business cash register. Content is encoded, and to get the key a user needs to do something—maybe paying money, maybe providing an e-mail address. DRM providers deliver the protection tools; it is up to content owners to set the conditions. ContentGuard uses a "multiple key" approach to content protection; anyone who received bootleg content would have to crack into it all over again. Thus, Singh explains, "even if a hacker cracks into a piece of content, he cannot distribute it."

So why isn't DRM ubiquitous? Two reasons. First, content owners are in the midst of a hard rethink about both pricing and distribution. Suddenly they are wrestling with issues of how to price three listens to a song, say, or a download of a low-resolution image that cannot be forwarded to others. "Content owners now are trying out different economic models for valuing content," says Singh, whose company provides DRM tools to, among others, John Wiley & Sons and Houghton Mifflin. "DRM opens many possibilities," he adds.

The second issue may be the more nettlesome: "The user experience has to hide the complexity of the protection technologies," says Singh. Users need to

JOSEPH ATICK

Biometrics

Visionics' Joseph Atick sees the wireless Web as key to widespread consumer adoption of biometric technologies.

In one sense, the field of biometrics—identifying individuals by specific biological traits—has already emerged. Large companies use fingerprint sensors for logging on to corporate networks, state driver's license authorities employ face recognition for capturing and storing digital photographs, and the first iris-scan-protected ATM in the nation was introduced in Texas in May 1999. Yet consumers have been reluctant to adopt the technology, and so far, it remains largely relegated to military and government applications.

But the emergence of another technology—the wireless Web—could soon change all that, according to Joseph Atick, president and CEO of Visionics, one of the leaders in face recognition technology. "Personal digital assistants (PDAs) and cell phones are becoming our portal to the world, our transaction devices, our ID and maybe one day our passport," says Atick. But entrusting these small gadgets with so much of our personal and financial information carries with it a great risk. "It is this need for security," Atick says, "that is going to drive biometrics."

And while the need for security is pushing the demand for biometric systems, other technology developments—increased bandwidth, new cell phones and handheld computers equipped with digital cameras—will create an infrastructure capable of putting biometrics into the hands of consumers. Visionics is taking advantage of this combination of need and infrastructure by developing tools to enable people to authenticate any transaction they make over the wireless Web using their own faces.

Even those in the industry who are skeptical of Atick's vision of a biometric-enabled wireless Web can't deny his ingenuity and ambition. At the age of 15, while living in Israel, Atick dropped out of school to write a 600-page physics textbook entitled *Introduction to Modern Physics*. "I was bored in school. I wanted to show the establishment I was serious about my interests," says Atick. "This book was my ticket to grad school." Remarkably, Stanford University accepted him at 16 into its graduate program, where he earned his master's degree in physics and PhD in mathematical physics.

After graduation, Atick applied his math skills to the study of the human mind. While heading the Computational and Neuroscience Laboratory at Rockefeller University, he sought to understand how the brain processes the abundance of visual information thrown at it by the environment. He and his colleagues discovered that the brain deals with visual information much as computer algorithms compress files. Because everyone has two eyes, a nose and lips, the brain extracts only those features that typically show deviations from the norm, such as the bridge of the nose or the upper cheekbones. The rest it fills in. "We soon realized there was tremendous commercial value to this process," says Atick. In 1994, he and colleagues Paul Griffin and Norman Redlich founded Visionics.

Based in Jersey City, N.J., Visionics develops and markets pattern-recognition software called FaceIt. In contrast to the main competing technology, which relies on data from the entire face, FaceIt verifies a person's identity based on a set of 14 facial features that are unique to the individual and unaffected by the presence of facial hair or changes in expression. In the past few years, the system has found success fighting crime in England and election fraud in Mexico.

In October, the company signed a merger agreement with Digital Biometrics, a Minnetonka, Minn.-based biometric systems engineering firm. Together they plan to build the first line of "biometric network appliances"—computers hooked to the Net with the capacity to store and search large databases of facial or other biometric information. The appliances, containing customers' identification data, can then receive queries from companies wanting to authenticate e-transactions. And while consumers will be able to access the system from a cell phone, PDA or desktop computer, Atick expects handheld devices to be the biggest

Others in Biometrics

Organization	Project
Viisage Technology (Littleton, Mass.)	Face recognition
Iridian Technologies (Marlton, N.J.)	Iris recognition
DigitalPersona (Redwood City, Calif.)	Fingerprint recognition
Cyber-SIGN (San Jose, Calif.)	Dynamic signature verification
T-NETIX (Englewood, Colo.)	Voice recognition

Photograph by NICK CARDILLICCHIO

market. Visionics is also working with companies in Japan and Europe to have FaceIt software installed on new Web-ready mobile devices so consumers can capture their own faces and submit encrypted versions over the Net.

Is that it for PINs and passwords? Atick predicts it will still be two to three years before PDA- and cell-phone-wielding consumers are likely to use biometrics instead. And as futuristic as his vision is, he is really striving toward something a bit old-fashioned. "Essentially, we are bringing back an old element of human commerce," says Atick—restoring the confidence that comes with doing business face to face. *—Alexandra Stikeman*

KAREN JENSEN

Natural Language Processing

The 1968 film *2001: A Space Odyssey* gave us a vision of the millennium based on the technological predictions of the day. One result: HAL 9000, a computer that conversed easily with its shipmates like any other crew member. The timing was off: In the real 2001, there's not a computer in the solar system as articulate as HAL.

But maybe it wasn't that far off. HAL's modern-day counterparts are catching up fast (sans the homicidal tendencies, one hopes). Already we have commercial speech recognition software that can take dictation, speech generation equipment that can give mute people voices and software that can "understand" a plain-English query well enough to extract the right answers from a database.

Emerging from the laboratories, moreover, is a new generation of interfaces that will allow us to engage computers in extended conversation—an activity that requires a dauntingly complex integration of speech recognition, natural-language understanding, discourse analysis, world knowledge, reasoning ability and speech generation. It's true that the existing prototypes can only talk about such well-defined topics as weather forecasts (MIT's Jupiter), or local movie schedules (Carnegie Mellon's Movieline). But the Defense Advanced Research Projects Agency (DARPA) is working on wide-ranging conversational interfaces that will ultimately include pointing, gesturing and other forms of visual communication as well.

Parallel efforts are under way at industry giants such as IBM and Microsoft, which see not only immediate applications for computer users who need to keep their hands and eyes free but also the rapid evolution of speech-enabled "intelligent environments." The day is coming when every object big enough to hold a chip actually has one. We'd better be able to talk to these objects because very few of them will have room for a keyboard.

Others in Language Processing

Organization	Project
Victor Zue (MIT Laboratory for Computer Science)	Conversational interfaces
Alexander I. Rudnicky (Carnegie Mellon)	Verbal interaction with small computers
Ronald A. Cole (University of Colorado)	Domain-specific conversational systems
BBN Technologies (Cambridge, Mass.)	Dialog agent

Getting there will be a huge challenge—but that's exactly what attracts investigators like Karen Jensen, the gung-ho chief of the Natural Language Processing group at Microsoft Research. Says Jensen: "I can't imagine anything that would be more thrilling, or carry more potential for the future, than to make it possible for us to truly interact with our computers. That would be so exciting!"

Such declarations are typical of Jensen, who at 62 remains as exuberant about technology's promise as any teenager—and just as ready to keep hacker's hours. Indeed, Jensen was one of the first people Microsoft hired when it opened its research lab in 1991. Along with colleagues Stephen Richardson and George Heidorn, she arrived at the Redmond, Wash., campus from IBM's Thomas J. Watson Research Center, where they had worked on some of the earliest grammar-checking software, and immediately started building a group that now numbers some 40 people.

In Redmond, Jensen and her colleagues soon found themselves contributing to the natural-language query interface for Microsoft's Encarta encyclopedia and to the grammar checker that first appeared in Word 97. And now, she says, they've begun to focus all their efforts on a unique technology known as MindNet. MindNet is a system for automatically extracting a massively hyperlinked web

Microsoft Research's Karen Jensen is heading an effort to give machines the ability to grok human language.

of concepts from, say, a standard dictionary. If a dictionary defines "motorist" as "a person who drives a car," for example, MindNet will use its automatic parsing technology to find the definition's underlying logical structure, identifying "motorist" as a kind of person, and "drives" as a verb taking motorist as a subject and car as an object. The result is a conceptual network that ties together all of human understanding in words, says Jensen.

The very act of putting this conceptual network into a computer takes the machine a long way toward "understanding" natural language. For example, to figure out that "Please arrange for a meeting with John at 11 o'clock" means the same thing as "Make an appointment with John at 11," the computer simply has to parse the two sentences and show that they both map to the same logical structures in MindNet. "It's not perfect grokking," Jensen concedes. "But it's a darn good first step."

MindNet also promises to be a powerful tool for machine translation, Jensen says. The idea is to have MindNet create separate conceptual webs for English and another language, Spanish, for example, and then align the webs so that the English logical forms match their Spanish equivalents. MindNet then annotates these matched logical forms with data from the English-Spanish translation memory, so that translation can proceed smoothly in either direction.

Indeed, says Jensen, who is now in the process of passing on the leadership of the group to the younger generation, MindNet seems to tie together everything they've been doing for the past nine years: "All we see is doors opening. We don't see any closing!" —*M. Mitchell Waldrop*

Others in Microphotonics

Organization	Project
Eli Yablonovitch (UCLA)	Photonic crystals for optical and radio frequencies
Susumu Noda (Kyoto University, Japan)	Optical integrated circuits
Axel Scherer (Caltech)	Optical switches, waveguides and lasers
Nanovation Technologies (Miami)	Integrated devices for telecom
Clarendon Photonics (Boston)	Filters for WDM

JOHN JOANNOPOULOS

Microphotonics

Light bounces off the small yellow square that MIT physics professor John Joannopoulos is showing off. It looks like a scrap of metal, something a child might pick up as a plaything. But it isn't a toy, and it isn't metal. Made of a few ultrathin layers of non-conducting material, this photonic crystal is the latest in a series of materials that reflect various wavelengths of light almost perfectly. Photonic crystals are on the cutting edge of microphotonics: technologies for directing light on a microscopic scale that will make a major impact on telecommunications.

In the short term, microphotonics could break up the logjam caused by the rocky union of fiber optics and electronic switching in the telecommunications backbone. Photons barreling through the network's optical core run into bottlenecks when they must be converted into the much slower streams of electrons that are handled by electronic switches and routers. To keep up with the Internet's exploding need for bandwidth, technologists want to replace electronic switches with faster, miniature optical devices, a transition that is already under way *(see "The Microphotonics Revolution,"* TR *July/August 2000).*

Because of the large payoff—a much faster, all-optical Internet—many competitors are vying to create such devices. Large telecom equipment makers, including Lucent Technologies, Agilent Technologies and Nortel Networks, as well as a number of startup companies, are developing new optical switches and devices. Their innovations include tiny micromirrors, silicon waveguides, even microscopic bubbles to better direct light.

But none of these fixes has the technical elegance and widespread utility of photonic crystals. In Joannopoulos' lab, photonic crystals are providing the means to create optical circuits and other small, inexpensive, low-power devices that can carry, route and process data at the speed of light. "The trend is to make light do as many things as possible," Joannopoulos says. "You may not replace electronics completely, but you want to make light do as much as you can."

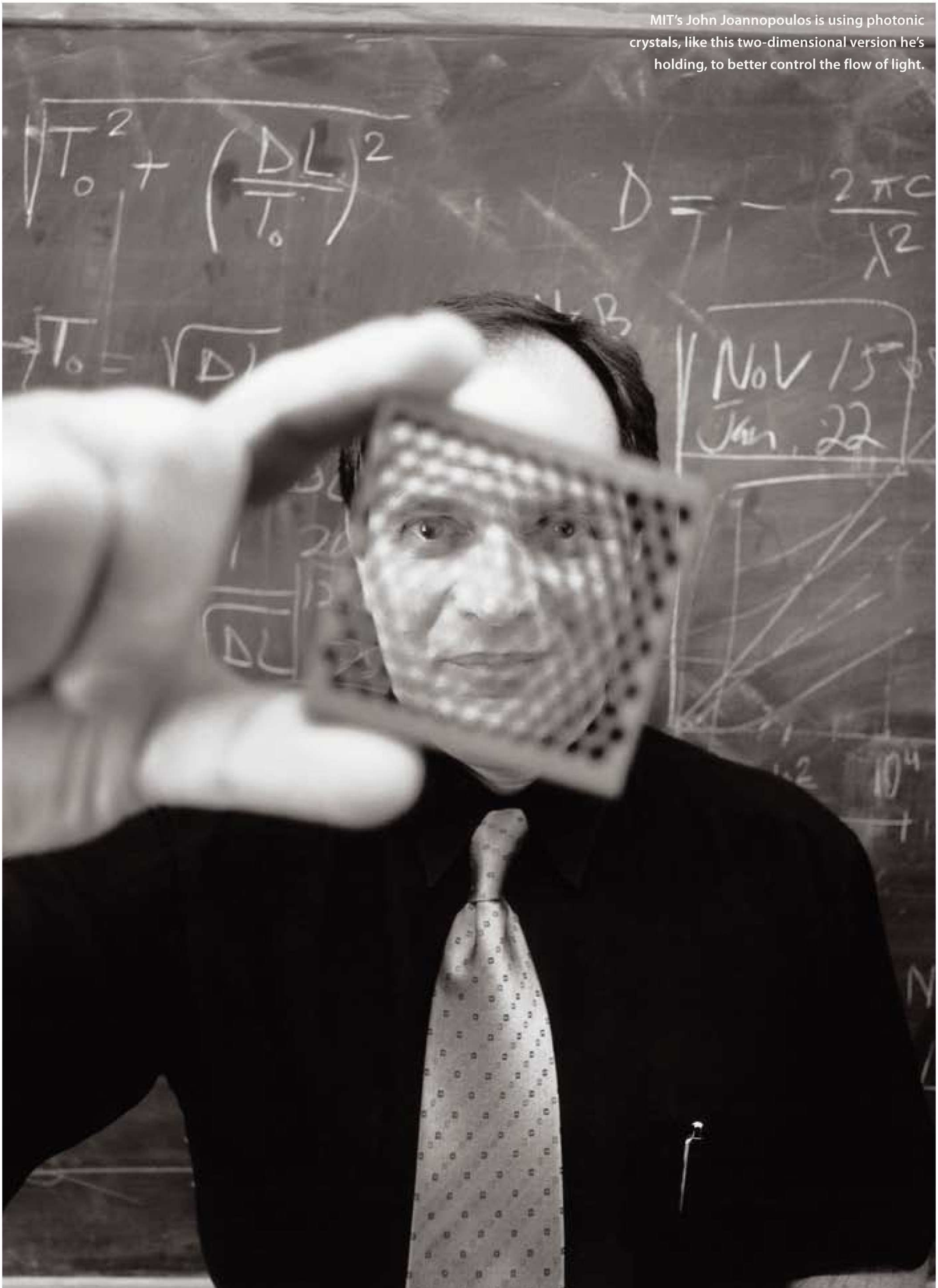
Conceived in the late 1980s, photonic crystals are to photons what semiconductors are to electrons, offering an excellent medium for controlling the flow of light. Like the doorman of an exclusive club, the crystals admit or reflect specific photons depending on their wavelength and the design of the crystal. In the 1990s, Joannopoulos suggested that defects in the crystals' regular structure could bribe the doorman, providing an effective and efficient method to trap the light or route it through the crystal.

Since then, Joannopoulos has been a pioneer in the field, writing the definitive book on the subject in 1995: *Photonic Crystals: Molding the Flow of Light*. "That's the way John thinks about it," says MIT materials scientist and collaborator Edwin Thomas. "Molding the flow of light, by confining light and figuring out ways to make light do his bidding—bend, go straight, split, come back together—in the smallest possible space."

Joannopoulos' group has produced several firsts. They explained how crystal filters could pick out specific streams of light from the flood of beams in wavelength division multiplexing, or WDM, a technology used to increase the amount of data carried per fiber *(see "Wavelength Division Multiplexing,"* TR *March/April 1999)*. The lab's work on two-dimensional photonic crystals set the stage for the world's smallest laser and electromagnetic cavity, key components in building integrated optical circuits.

But even if the dream of an all-optical Internet comes to pass, another problem looms. So far, network designers have found ingenious ways to pack more and more information into fiber optics, both by improving the fibers and by using tricks like WDM. But within five to 10 years, some experts fear it won't be possible to squeeze any more data into existing fiber optics.

The way around this may be a type of photonic crystal recently created by Joannopoulos' group: a "perfect mirror" that reflects specific wavelengths of light from every angle with extraordinary efficiency. Hollow fibers lined with this reflector could carry up to 1,000 times more data than current fiber optics—offering a solution when glass fibers reach their limits. And because it doesn't absorb and scatter light like glass, the invention may also eliminate the expensive signal amplifiers needed every 60 to 80 kilometers in



MIT’s John Joannopoulos is using photonic crystals, like this two-dimensional version he’s holding, to better control the flow of light.

Photograph by JOHN SOARES

With his "aspect-oriented" approach, Xerox PARC's Gregor Kiczales is making computer programs easier to write and maintain.

today's optical networks *(see "Blazing Data,"* TR *November/December 2000)*.

Joannopoulos is now exploring the theoretical limits of photonic crystals. How much smaller can devices be made, and how can they be integrated into optical chips for use in telecommunications and, perhaps, ultrafast optical computers? Says Joannopoulos: "Once you start being able to play with light, a whole new world opens up." —*Erika Jonietz*

Others Untangling Code

Organization	Project
Mehmet Aksit (University of Twente, the Netherlands)	Composition filters
Karl Lieberherr (Northeastern University)	Adaptive programming
IBM Research (Yorktown Heights, N.Y.)	HyperJ system for Java programming
Mira Mezini (Univ. of Siegen, Germany)	Enhancing modularity and reusability of A-O software

GREGOR KICZALES

Untangling Code

Pity software engineers. With the touch of a button, their programs let us make global fixes in a long text, say, or a spreadsheet, yet programmers often need to correct their own work one tedious line at a time. That irony isn't lost on Gregor Kiczales, principal scientist at Xerox's Palo Alto Research Center (PARC) and professor at the University of British Columbia in Vancouver—and he has a fix in mind. Kiczales champions what he calls "aspect-oriented programming," a technique that will allow software writers to make the same kinds of shortcuts that those of us in other professions have been making for years.

One such "crosscutting" capability is logging—the ability to trace and record every operation the application performs. Since any given command might touch down on functionally unrelated areas of the code, programmers now must make a rule, such as: "When adding a new function to this application, always put a trace statement in." Of course, the rule works only if people remember to follow it.

Other crosscutting capabilities include security and synchronization—the ability to make sure that two users don't try to access the same data at the same time. Both require programmers to write the same functionality into many different areas of the application. Even a modest-sized application can easily present 100 crosscutting issues.

Programmers try to track these instances of repetition, so that when a capability needs to be changed or upgraded, it can be done uniformly throughout the program. But keeping track of crosscutting concerns is an error-prone process. Forget to upgrade just a few of these instances, and your code starts collecting bugs. "We're forced to keep track of everything in our heads," says Kiczales.

Kiczales' proposed solution is to create a new category within a programming

Photograph by MARK GILBERT

language called an "aspect." Aspects allow programmers to write, view and edit a crosscutting concern as a separate entity. Once the programmer is happy with it, a single keystroke will weave the aspect into the code wherever it is needed. It's a smart, intuitive, neat solution to an old problem. And what's good for programmers is good for the rest of us: Widespread adoption of aspects holds out the promise of less buggy upgrades, shorter product cycles and, ultimately, better and less expensive software.

The idea of aspects has been around for many years and with many different names. It's called "adaptive programming" at Northeastern University, "subjective programming" at IBM, "composition filtering" at the University of Twente in the Netherlands and "multidimensional separation of concerns" elsewhere. But unlike these other research projects, Kiczales and his team at PARC have taken the concept out of the lab and into the real world by incorporating the idea of aspects into a new extension of the programming language Java. The beta version of this extension (called AspectJ) is available for free at www.aspectj.org, and Kiczales plans to make release 1.0 ready by June. "Major changes in programming methodology can take 30 years to gain widespread acceptance," he says. Making aspects an extension to an existing standard should, he predicts, "cut the cycle by 15 or 20 years."

While Kiczales admits the tools are still a little raw, there are nevertheless about 500 users of AspectJ today—most of them finding existing tools inadequate for creating long, complicated programs in Java. Some have already found AspectJ so solid that they've used it in production. One of these is Checkfree.com, a company that makes software for automatic bill payment. Checkfree sells both C++ and Java versions of the software. Rich Price, senior engineer, estimates that AspectJ allowed his team to implement an important crosscutting capability in the Java version in four programmer-hours, whereas the C++ team, with no aspect-oriented programming tools at their disposal, took two programmer-weeks to do the same thing. Using aspects, he says, "I make one change, in one place, and it gets woven in where it needs to be. I love that."

By folding their ideas into a practical Java extension, Kiczales and his team hope to make aspects part of the vernacular of programming languages. "AspectJ lets programmers work more quickly and at a higher design level," says Kiczales. "We've learned that crosscutting concerns are actually not hard to work with—once you have the proper programming support." —*Claire Tristram*

JORDAN POLLACK

Robot Design

Robot builders make a convincing case that in 2001, robots are where personal computers were in 1980—poised to break into the marketplace as common corporate tools and ubiquitous consumer products performing life's tedious chores. One big obstacle remains: It is expensive to design and make robots smart enough to adapt readily to different tasks and physical environments, the way human beings do.

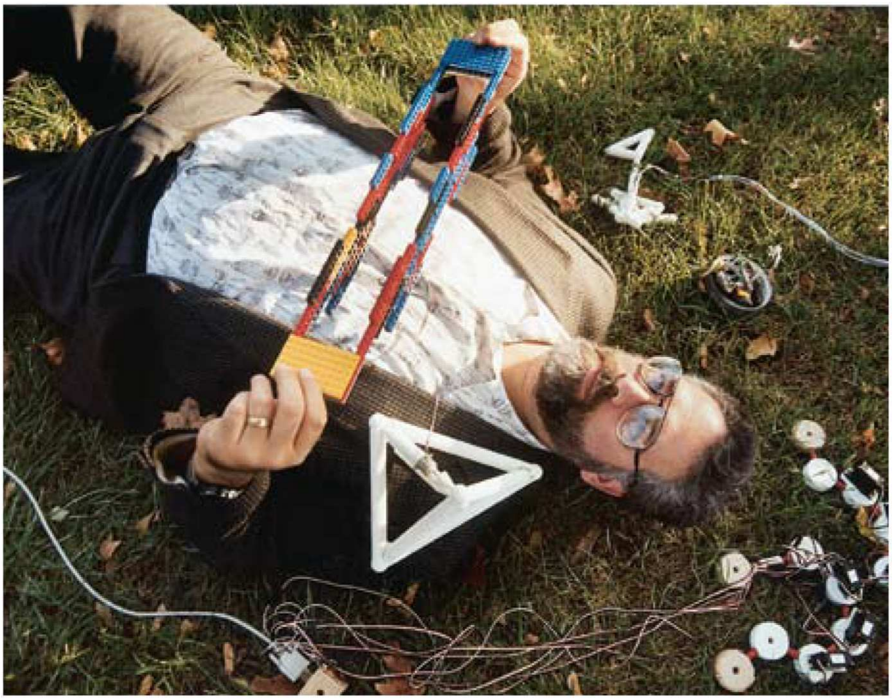
That's the reason why robotics have, so far, found a commercial niche only in simple and highly repetitive jobs, such as working on an automotive assembly line, or mass-producing identical items, such as toys. The challenge for builders of robots is to build more complexity into them without the huge investment of custom-tailoring each robot for a different task.

One promising approach is to fully automate the design and manufacture of robotics by deploying computers to conceive, test and even build the configurations of each robotic system: in short, to use robots to build robots. Last year, in a cramped lab at Brandeis University in Waltham, Mass., Jordan Pollack demonstrated how this automated robotic design and manufacturing might work.

Pollack, an associate professor of computer science, together with postdoc Hod Lipson, directed a computer to design a moving creature using a limited set of simple parts: plastic rods, ball joints, small motors and a "brain" (neural network). The computer—using an algorithm inspired by biological evolution—"evolved" hundreds of generations of potential designs, killing off the sluggish and refining the strong. Eventually, several of the fastest and fittest came to life,

Others in Robot Design

Organization	Project
Sarcos (Salt Lake City, Utah)	Robots for industry, medicine, Hollywood
iRobot (Somerville, Mass.)	Household communications robot
Humanoid Interaction Lab (Tsukuba, Japan)	Interactions between humanoid robots and humans
MIT Artificial Intelligence Lab (Cambridge, Mass.)	Machine learning, robot legs, faces
Robotics Institute (Carnegie Mellon)	Mobile robots and face recognition


Brandeis' Jordan Pollack with some of his "creatures" designed by robots.

Photograph by JOHN GOODMAN

manufactured in a rapid-prototyping machine. Pollack and Lipson snapped on the motors, and the creatures moved.

"I think the important point of our coevolutionary design and automated manufacturing for robotics is to get small-quantity production to be economical," Pollack says. He predicts that the evolutionary approach to robot building could lead to the first cheap industrial robots in five to 10 years. "If we are successful, we could see an industry within a decade which makes low-quantity custom machinery worth more than it costs to make."

For now, Pollack's "automated" process still takes plenty of human intervention and money: Pollack and his colleague wrote the computer program and spent $50,000 on the human-built fabricating device. Still, the team's advance, reported last August in the journal *Nature,* garnered wide publicity. "The importance is symbolic," says Hans Moravec, principal research scientist at the Robotics Institute at Carnegie Mellon University in Pittsburgh. "You have systems that develop robots out of thin air, not by humans. In the future, there will be real robots designed that way."

Pollack's design and manufacturing methods have plenty of competition. Academic and industrial labs around the world are busy building new generations of robots. Within this decade, experts predict a steady evolution in commercial utility robots: robots that can clean floors and pick up things. "There will be a mass market for robots," suggests George Bekey, founder of the robotics lab at the University of Southern California in Los Angeles. "This next decade will be the decade of the robot."

Before robots reach out into the everyday world of business and the household, though, they will need their own version of Moore's Law: becoming dramatically more affordable and powerful over time. In spite of intriguing experiments such as Pollack's, designing even relatively simple robots is a painstaking task. In Japan, for example, Honda has spent over 14 years building a humanoid robot able to walk, open a door and navigate stairs.

A walk around Pollack's lab suggests, perhaps, a better way to design robots. On a workbench sits one example of his computer-designed and computer-buildable machines; it moves eerily like an inchworm. Pollack trims excess plastic from a newly fabricated plastic-rod machine, oblivious to the shavings collecting on his shirt and around his chair. In a few years Pollack may well evolve a cheap robot able to sweep those shavings off the floor. —*David Talbot*

STEPHEN QUAKE

Microfluidics

The forces of physics move oceans, mountains and galaxies. But applied physicist Stephen Quake uses them to manipulate things on a vastly reduced scale: tiny volumes of fluids thousands of times smaller than a dewdrop. Microfluidics, as Quake's field is called, is a promising new branch of biotechnology. The idea is that once you master fluids at the microscale, you can automate key experiments for genomics and pharmaceutical development, perform instant diagnostic tests, even build implantable drug-delivery devices—all on mass-produced chips. It's a vision so compelling that many industry observers predict microfluidics will do for biotech what the transistor did for electronics.

Quake's 11-person lab at Caltech is not the only outfit bent on realizing this vision. Over the past decade or so, scores of researchers have set out to build microscale devices for many of the basic processes of biological research, from sample mixing to DNA sequencing. But many of those groups have run into roadblocks in developing technology that can be generalized to a broad range of applications and would allow several functions—such as sample preparation, DNA extraction and detection of a gene mutation—to be integrated on a single chip. Moreover, some of the manufacturing approaches involved, particularly silicon micromachining, are so expensive that experts in the field question whether products relying on these techniques could ever be economical to manufacture.

Quake's group is one of several now working their way around these obstacles. Last spring, the team unveiled a set of microfabricated valves and pumps—a critical first step in developing technology general enough to work for any microfluidics application. And to make microfluidic devices cheaper, Quake and others are casting them out of soft silicone rubber in reusable molds, using a technique called "soft lithography." The potential payoff of these advances is huge: mass-produced, disposable microfluidic chips that make possible everything from drug discovery on a massive scale to at-home tests for common infections.

Because microfluidics is so promising and yet so technically frustrating, expectation and hype have sometimes outpaced the development of viable technology. Yet Quake and his group have consistently turned out elegant devices that actually work. First was a microscale DNA analyzer that operates faster and on different principles than the conventional, full-sized version, then a miniature cell sorter and most recently, those valves and pumps, described last April in the journal *Science*. All this while regularly publishing important findings on the basic physics of biological molecules.

If Quake seems adept at straddling fields—in this case science and technology—perhaps it's because that's exactly the sort of challenge he has long craved. Even as an undergraduate at Stanford University, where he earned bachelor's and master's degrees simultaneously in only four years, Quake worried that physics was "somewhat finished" as an experimental science, that it was hard to find the field's frontiers. A pioneer at heart, Quake started looking to tackle questions that lay at the boundaries between disciplines. As he recalls: "It was completely obvious, even to an outsider, that biology was going through this period of incredible growth and intellectual excitement, and there were going to be big questions asked and answered, and the frontiers were advancing at a tremendous rate in all directions."

After Quake finished his doctorate in theoretical physics at Oxford University,

Others in Microfluidics

Organization	Project
Aclara BioSciences (Mountain View, Calif.)	Genomics and drug screening
Caliper Technologies (Mountain View, Calif.)	DNA, RNA and protein assays
Cepheid (Sunnyvale, Calif.)	DNA analysis
Micronics (Redmond, Wash.)	Diagnostics and chemical analysis
TECAN (Hombrechtikon, Switz.)	Drug discovery


Caltech's Stephen Quake has set his sights on the microscale, building tiny disposable devices that could revolutionize biotechnology.

he went back to Stanford as a fellow working on the physics of DNA. When Caltech's applied physics department hired him in 1996, Quake says, "it was an experiment for them"—he was the first faculty member in the department with a biological bent. So far, the experiment seems to be going smoothly; this past summer, at only 31, Quake got tenure.

Quake's inventions are also thriving in industry, through a startup called Mycometrix. Founded in 1999 by Quake, two of his college classmates and a consultant, the South San Francisco-based company has licensed all of Quake's microfluidics patents from Caltech. When *TR* went to press, the company was planning to deliver its first microfluidic devices to selected university researchers and industry partners by the end of 2000, and was hoping for a commercial release by the end of this year or early 2002. The competition will be intense. Several startups and even electronics giants like Hewlett-Packard and Motorola are getting in on the game. But to date, only one of Mycometrix's competitors has brought a microfluidic product to market.

Although Quake's work is rapidly flowing into the commercial marketplace, it's still the very early stages of science and technology development that interest him the most. And though he has built quite a reputation as a technologist, he hopes soon to focus more of his attention on some of the most pressing questions in basic biology: How do the proteins that control gene expression work? How can you do studies that cut across the entire genome? "Now that we've got some pretty neat tools," Quake says, "we're going to try and do some science with them." Quake's ability to work in areas from basic research to hot commercial markets make him a prototypical innovator. And the same versatility makes microfluidics a field to pay close attention to in the next few years. *—Rebecca Zacks*