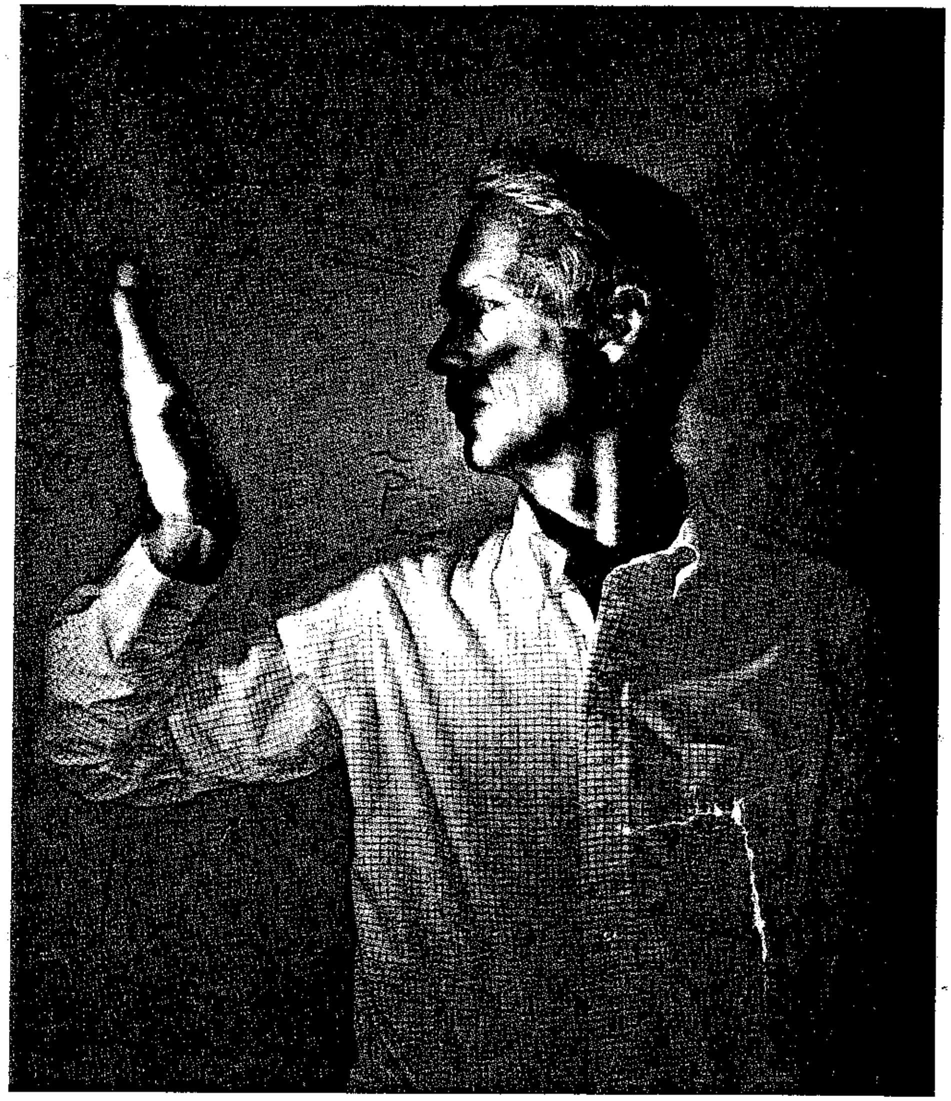
INTERVIEW

Striding to his Caltech office, John Joseph Hopfield spies the silvery trail of a snail that had been scouting for food at dawn. The telltale strip goes in a straight line, a circle, and then a straight line again. That, says neural-network theorist Hopfield, means "the wind changed while the snail was following the scent." He ought to return again before daybreak, he muses, with video camera and spotlight to track the snail's movements and correlate them with shifts in the wind.

Strange activities for a computer theorist, perhaps, but Hopfield has little respect for boundaries. Snails are central to his latest project: working out the math of a system that will smell the location of an object—as does a snail heading for breakfast. It's all part of Hopfield's neural networking, an approach to computer architecture whose goal is a machine that may even imitate human consciousness.

Conventional computers are superhuman only in the speed they apply to tedious, brick-by-brick logic, sorting mountains of spoon-fed data. Hopfield's systems learn and judge for themselves, and he's confident they'll eventually simulate emotions and creativity. If computers someday paint, compose music, write novels, and run governments, Hopfield will have to take some of the blame.

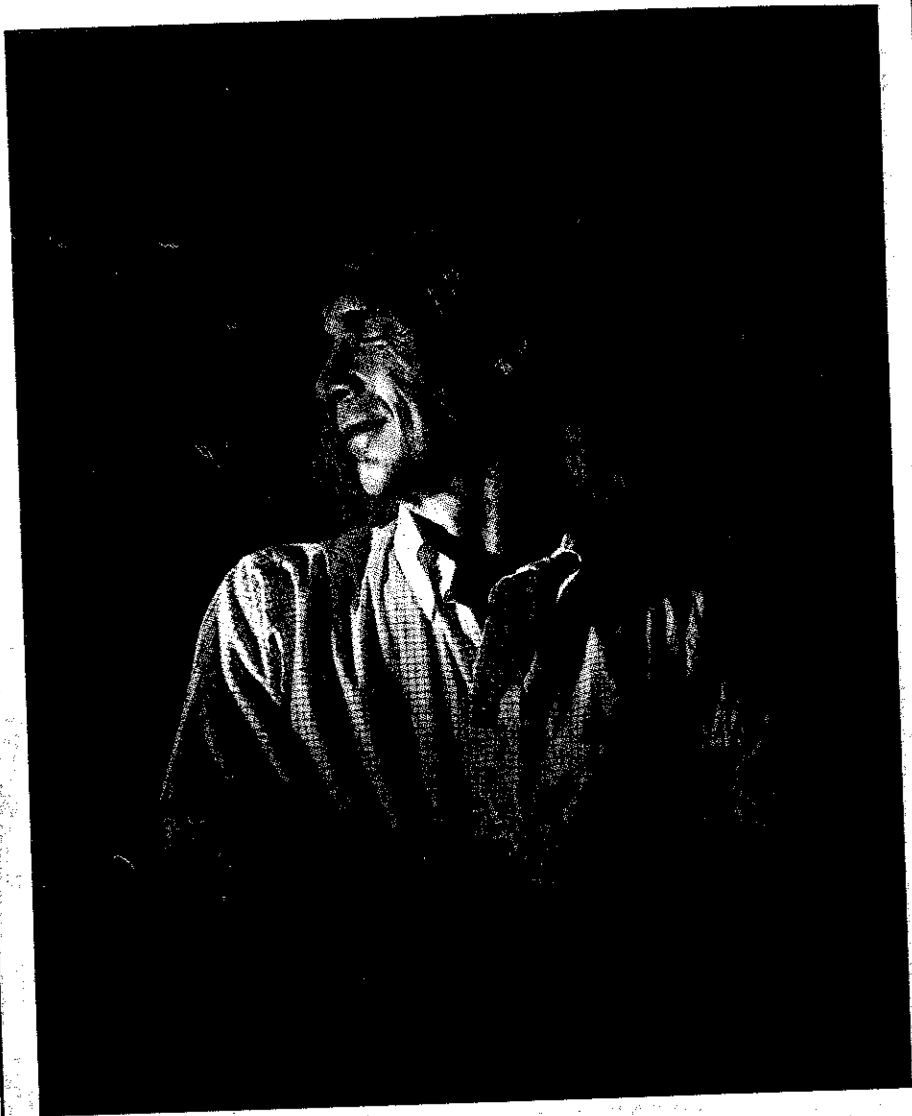
The son of a Polish physicist, Hopfield inherited his father's can-do philosophy that everything in life—from smelling roses to the workings of the mind—can be fathomed with math and logic. So when artificial intelligence (AI) in digital computers reached a roadblock in the late Seventies as it bumped against the limits inherent in its design, Hopfield opened a new way. He worked out a math model of associative memory in large networks that functioned in a way equivalent to neurons in real brains. Efforts to engineer neural nets into silicon circuitry began at Caltech, Bell Labs, and



JOHN J. HOPFIELD

With an array of electronic sensors that measure the physical things being done to them, you have the means whereby consciousness could be an issue.

PHOTOGRAPHS BY DAN WINTERS



A COMPUTER COULD BECOME TRULY SELF-REFERENTIAL; IT WOULD HAVE A WAY TO MEASURE ITS OWN HEARTBEAT.

MOTTO:
"Let me define it operationally."

YES, BUT CAN THEY OUT-CURSE A PARAKEET?
Neural nets can now play backgammon, recognize faces from parts of photos, identify airplanes on radar, learn languages, score credit for loans and mortgages, analyze fingerprints, read databases, calculate aerodynamic flow, schedule airline flights, test Pap smears, detect abnormal heartbeats, predict stock indexes, diagnose symptoms and prescribe medication, aim missiles, read handwritten zip codes, talk from written texts, play Ping-Pong, and read lips. Soon systems will check the faces of individuals going into secure buildings, enable industrial robots to pick among parts to fashion a product, someday imitate consciousness or be conscious.

elsewhere. By 1988, even the grand guru of AI, Marvin Minsky of MIT, at first skeptical, predicted that "neural technology is the way of the future." A defense official said neural-modeling technology would be "more important than the atom bomb."

Hopfield's systems compute by association, detect patterns, and form judgments. Like the human brain, they learn, generalizing from examples. Unlike strictly logic-based AI, they handle the random perceptions of the everyday world—recognizing faces and objects and understanding human speech. Like humans, they have hunches and intuitions. A conventional computer will struggle to make sense out of *bat, ball,* and *diamond.* A neural network will *catch* the ball in its *glove.*

No wild-eyed visionary, but a sober mathematician, Hopfield nonetheless predicts that we will have computers that will either imitate consciousness or be conscious—depending on your definition of that concept. So far, nearly all of these systems are software run on conventional computers that only simulate in slow motion the performances of neural-net hardware. Several companies, however, have made prototype neural chips.

Sample neural cubes decorate Hopfield's desk: jewel-like squares the size of a quarter, gold wiring glinting against blue borders. Like the brain's neurons and synapses, neural chips respond and send signals according to the strength and frequency of the signals passing through them rather than simply switching on or off in digital fashion. Actual neural nets built so far are much less powerful than a cockroach's brain. Yet when neural chips are mass produced and hardware built, they should compute millions of times faster than conventional machines.

Hopfield is a tall, lanky figure who spews ideas with great precision and vitality. As interviewer Anthony Liversidge crossed the door of his office, Hopfield sprang up from a knee chair at his computer, shook hands vigorously, and gave his full attention. Hopfield has no financial participation in the infant university-military-industrial neural-net complex his ideas have spawned. He has, however, won his share of prizes, from a MacArthur Foundation grant in 1983 to the Wright prize Harvey Mudd College awarded him, he jokes, for "being a dilettante."

Omni: How do snails in real life compare to your computer models?
Hopfield: My mathematical slugs are simple neural networks that correspond with the real slug's anatomy. They can easily produce the same kinds of learning behavior as snails. My colleagues at Bell Labs have stud-

CONTINUED ON PAGE 88

CONTINUED FROM PAGE 76

ied real slugs and found oscillations in activity in the brain area that processes olfactory signals. We're hoping this oscillation corresponds to those we see in mammalian systems. Every time you take a sniff, the olfactory bulb, the first stage of olfactory processing, bursts into a kind of oscillation, a rapid excitatory and inhibitory activity of groups of neurons. Those oscillations are part of the computation. Other parts of the brain oscillate, too.

Omni: How does oscillation process information or yield answers?

Hopfield: Or code information in some fashion? For example, if different parts of the brain oscillate at the same frequency but in different phase, information is contained in that difference. Maybe the oscillation is a carrier, a way of several pieces of information on one communication pathway. Perhaps this oscillation is used to mark information so that two things in different places in the brain are oscillating in the same way because they represent different parts of the same object. We've used oscillations as a way of amplifying and selecting information.

Omni: Would oscillation work to compare samples at different times?

Hopfield: Possibly. The sensor might want to take samples at different times because the smells in a room fluctuate. Otherwise, it would get an average smell that wouldn't tell you much about what was in the room. Or it might be useful as an amplifier of signals. The oscillation in the olfactory bulb of mammals, in the level of electrical signals in the neurons, goes on every time you sniff, breaking into about 40 cycles per second, 40 hertz. There is also the oscillation of breathing itself—say, 1 hertz. The slug oscillates about once a second, and it isn't clear if this is used like the mammal breathing cycle to make independent samples of the air.

It would be astonishing if oscillation were a mere epiphenomenon, but there's not yet a definitive statement about what it does in processing. One paper argues it is the beginning, the essence of consciousness. Oscillation represents richer dynamics, and computation *is* dynamics. Dynamics, the change of activity with time, is better han true-false logic for describing neural computation. Harnessing oscillation is an important challenge.

Omni: But will you be able to build a system that smells?

Hopfield: Oh yes, even a system to pull apart mixed smells just as animals can. Others have used neural nets to identify a smell in isolation but never in a mixed environment. Their simple olfaction model has one test: It presents one single odor to see if an animal can decide if it's good or bad by moving toward or away from it. But in the natural world, odors are usually mixed up. I'm working out how the system deals with that complexity.

Previously we thought that a single odor is the same problem as taste, a proximal sense. You decide what's in your mouth—is it a mushroom? But olfaction is a form of remote sensing. That's why scents are intermingled. Now if the mixture were constant, there'd be no way of unscrambling the odors coming from different objects. But if odors are intermixed in a fluctuating way, you can possibly unscramble them because the relative amounts are changing. In the simplest case, when the background is fixed and the template odor comes and goes, you can evaluate whether what comes and goes has the same ratios of components as the template. If you go into a kitchen that stinks of cabbage, say, 30 seconds later that odor has disappeared. Then if the cook puts something else under your nose, you smell it in a relatively normal way.

> ❛Why are people put together as they are? In some sense, it's an accident. You could have equal intelligence in something that looks like a cow.❜

Omni: If you could equip a robot with smell, how close would that be to human brain activity?

Hopfield: Smelling for humans is extraordinary for the kinds of memories it evokes. Gee, that smells like grandmother's house, and so on. To copy humanlike behavior, you'd need not just the sense of odor identification, but also to combine it with the rest of knowledge. Some sets of memory are strongly odor associated and often emotionally charged. Smell is linked to emotion much more than vision—for reasons relating to sex, fighting, and food.

A problem in making humanlike systems is that there's no simple correspondence between the artificial math model and real neurons. We can already imagine vision systems that do what we do when we see, including the "errors." Visual illusions, for instance, are caused by improper shortcuts in the algorithms biology uses—things that are wrong. You're not going to get illusions in an artificial system until it has an uncanny similarity to human vision. It will be getting close when the engineered system also suffers from biology's mistakes, has biology's illusions.

Omni: Will neural networking be more influential than the atom bomb?

Hopfield: They will certainly be more used! There isn't much technology yet, just the algorithms we run on digital machines to simulate neural networks. Real neural-net hardware will be much faster than emulating neural networks on digital machines. People are doing things: Du Pont has plastic sheets rolling out rapidly while an engineer tunes the process for quality. Du Pont is using networks in some aspects of measuring and predicting product quality.

Omni: That's pretty mundane.

Hopfield: Utterly mundane, but if you're turning out millions of dollars of product a year and a neural-net algorithm helps you, you know neural nets are not just imagination. Process engineers can be concerned with things like the texture of materials, fiber for fabric. Texture is slightly nebulous—it isn't a nice physical measurement. Texture is a more ethereal measurement. You look and judge: No, it's not quite right. A neural system can learn to recognize texture in some sense, even though you haven't given it a set of rules. Unlike a digital system, you can't quite tell it what to do; it has to decide for itself.

Omni: What other kinds of systems have a big future?

Hopfield: Practical databases. People are working on networks to recognize English words in natural speech or to take written words and speak them naturally. Speech is tough. There's a lot of natural variation. It is hard to give a rule for what a sound wave should be so that it can recognize, say, the word *six*. But give a network many, many examples of *six* and *no six*, and after a while it constructs its own procedures and becomes very effective at recognizing the difference. Getting a machine to generate speech is easier than getting it to listen to speech.

Turning typed text into speech is easier. *Speak and Tell*, made by Texas Instruments, has a set of rules to get from letters to pronunciation. There's a lot less natural variation in typed text. At Caltech, we've been working on neural hardware for a speech-interpreting network. We talk into it and it recognizes the word we said. We work with a small vocabulary. If you can do it small, you can do it large. Question is, can you do it with all the natural varia-[illegible]? You, Anthony, speak with a resid-[illegible]ritish accent that's quite different from a ten-year-old girl's from the South. The network has to solve what is similar between the two.

Omni: Will we soon get a phone anyone can speak a number into and it will dial?

Hopfield: That is totally doable now at great expense. But can you do it for ten bucks on a single low-electric power chip? That's the real intellectual and technological challenge. Intel is doing interesting things. They've recently marketed a neural-net chip with "synapses," 64 neurons and 8,192 continuously adjustable connections—synapses. It probably costs about ten dollars to make. Previously, chips needed already-made connections or else connections of discrete strengths, like zeros and ones. In use, such connections are either made or not made, unlike the continuously adjustable connections of biology.

In a neuron, an action potential arises on an axon terminal, then releases some neurotransmitter over to the other side to the dendrite, and an electric[illegible]urrent flows into the dendrite. How [illegible] electrical current flows depends on how much transmitter is put out, how many receptors are on the other side, and so on. There is modification, and that modification, for example, is what goes on when you learn. The strength of that synapse is fairly adjustable.

That is what the Intel chip represents. The connections in the chip don't have to be fully turned on or off. With a certain voltage at the gate, the transistor is partially turned on and a partial connection made. The resistance is adjustable according to the charge at the gate. Before this, the control of these charges on the gates was not good. Either you had a lot of charge and it was turned all the way on and a 1 was stored, or the charge was not enough, and you stored a zero somewhere. Intel's technology allows a partial charge, providing a way of controlling the connection in a continuously adjustable way.

Omni: Will simulated synapses ever mimic the internal workings of the brain cell—second messengers, protein syn[illegible] and so on?

Hopfield: That's not the way electronics will go. Biology has all those things available and so uses them very cleverly in the way it gets neurons to compute. We will use the physics that is available in the electronic chip in the same way that neurobiology capitalizes on the structure of the cell.

Omni: Mathematician Roger Penrose says you need quantum mechanics to explain consciousness. Do you agree?

Hopfield: There has long been a romantic notion among physicists such as Niels Bohr, Eugene Wigner, and others that quantum mechanics is the secret to the complications and richness of thought and neurobiology. I fundamentally disagree. The real mysteries of neurobiology are essentially problems described by classical physics operating in large systems.

To look at two atoms colliding is not interesting. But with 10 to the 43 atoms colliding, all the complications of wind and weather come into being. A simple set of equations—but describing a large system—can produce a hugely complicated set of phenomena completely unlike what you'd have expected from the microscopic laws if you hadn't studied the hell out of them mathematically. These collective or large-system phenomena are often astonishing, but they come from the huge numbers of molecules or synapses, not the intrinsic complexity of the underlying physics.

There is nothing mystical in the collective behavior of large systems, and the brain is one. Many physicists have made the wrong choice about what's important in neurobiology. Penrose is the most recent example of a noble but wrong-headed line.

Omni: But can you be certain quantum mechanics doesn't affect the brain?

Hopfield: There's simply no evidence for it and considerable analysis to show why this should be true. Any thinking chemist or condensed-matter physicist takes the same position I do. Penrose never worked on large, complex systems whose behavior now is determined by many details that happened in the past. Why are humans intelligent? In some sense, it's an accident. You could have equal intelligence in something that looks like a cow. Biology as we see it has a huge number of frozen accidents in it. To understand the most evolved part of biology, clearly the intelligent mind, you have to know something about the frozen accidents.

Omni: Have you proved your point by making computers that can be called conscious?

Hopfield: They are much more like biology, but, of course, you could say they are still only programs in digital machines. They as yet have no consciousness. But what *is* consciousness? The term is so ill-defined. I can conceive of nothing at present as having consciousness, because I'd have to be able to define consciousness to describe whether it was present. Three years ago, I started asking friends what their attitude was about it. Richard Feynman's view was that consciousness is not a scientific subject because he couldn't define it well enough to get his hands into it and ask, "Is this object conscious?"

Omni: So physics per se can't define consciousness?

Hopfield: It's the old Turing problem. If you communicate with a keyboard at a terminal that communicates with something at the other end of a line, is the thing you're communicating with conscious? I can easily conceive of a digital machine clever enough to have a dialogue with you for, say, five minutes. You'd have horrible trouble deciding what was at the other end. Or suppose you had a playful computer-science student at the other end saying, "I'm going to be machinelike"?

Consciousness has something to do with attention, but that's a vague start and not good enough.

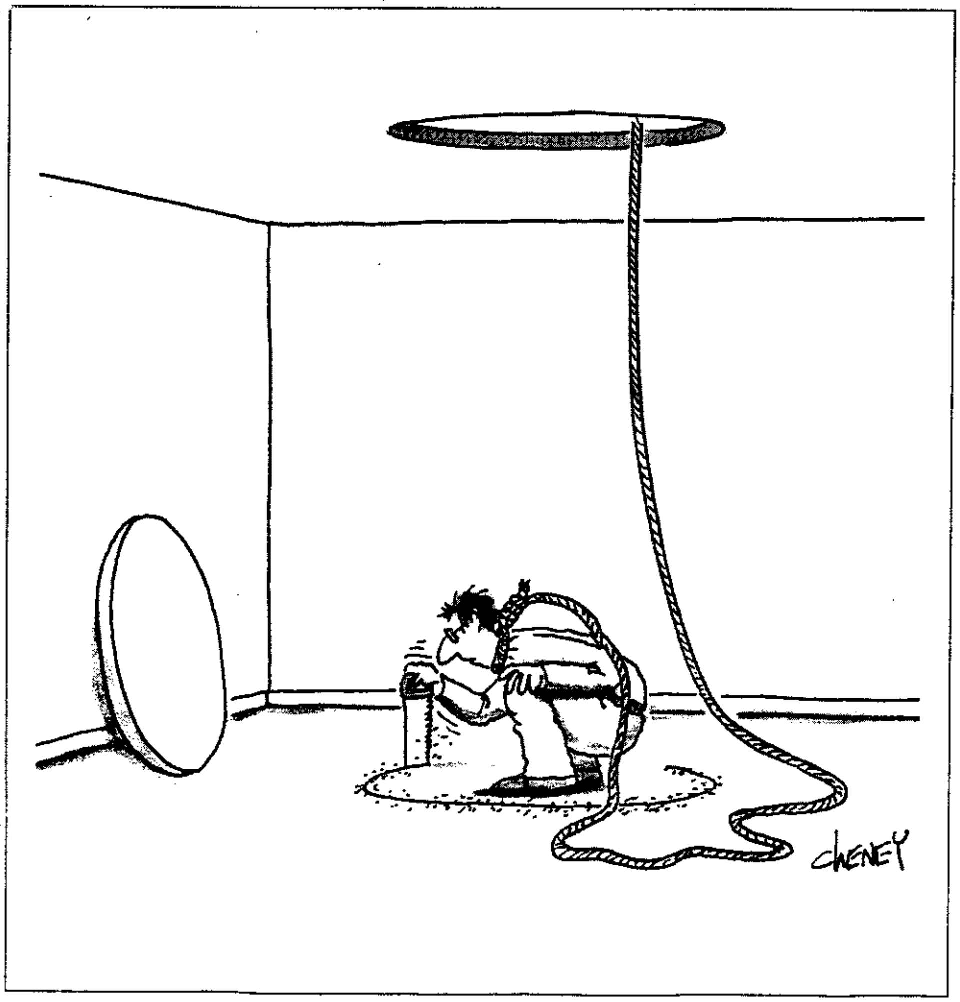
Omni: If attention is a part of consciousness, much of the human race may not be conscious.

Hopfield: A large part of what humans do is highly intelligent behavior but not conscious. You drive home along a route you know well and you have a choice at each corner to turn left to deviate from your usual route, and you don't; you're unconscious of your choices. Consciousness may be a simple add-on somewhere along the line. Marvin Minsky views consciousness as not very interesting because most powerful computations you do in a nonconscious fashion.

I often put some research problem away and don't think of it for a while and return to it to find it's much more developed than it was. Intelligent processing has been going on. While consciousness must be in some sense a collective phenomenon, that doesn't explain what it is. It only explains where to look for it. It's collective within the physics of the operation, something that comes from the very large number of nerve cells and not Planck's Constant.

Omni: You mean consciousness is just the result of having so many neurons in the cortex—a hundred times as many as rats do?

Hopfield: There are certain behaviors that don't take place in a small number but that in large numbers are fundamentally different. Look at the social interaction of two people. There's nothing in the behavior of a pair of people conveying the idea that if a thousand people get together, a riot can take place.



A riot can only take place above a certain size group. It isn't because people interact differently, but the consequences of those interactions are different when you have large rather than small numbers. Physics is full of these phenomena for economic systems, weather, and other things.

Omni: Isn't consciousness shown by the ability to interact with oneself?

Hopfield: That's a part of the story, but how do you tell whether you think about yourself or not? The issue partly involves the fact that there exists a physical as well as a mental you. Your arm is not just a word, it's a physical object. The interaction between symbols and physical objects is part of the difficulty in describing consciousness. If you insist on having a dialogue only on a computer line and describe everything only with language, the physical world "out there" is only apparent in terms of words. But when humans think and experience the world, they have independent sensors of touch, vision, and smell that give them direct descriptions. Then the world is not just words.

Omni: Isn't a computer that says, "Help, I'm being damaged!" conscious?

Hopfield: For the computer to actually do so, it would need sensors that observe or measure the physical things being done to it. With an array of such sensors, you begin to have the means whereby consciousness could be an issue. The computer could become truly self-referential; it would have a way to measure its own heartbeat.

Omni: Do you dare advocate building emotions into machines?

Hopfield: All higher animals have emotions that serve a biological function. I think I understand crudely how to insert the essential idea of them into physical systems. They're not built particularly easily in hardware, but the principle is relatively simple. It goes back to the question, "Why, when you are hungry, do many things remind you of food that otherwise wouldn't?"

Omni: But hunger isn't an emotion like regret, fear, or hope.

Hopfield: What do you mean by hope? Somebody who has hope will take a persistently positive view of a situation and do actions identifiably in one class. Someone without hope will take a different class of actions.

Omni: Isn't that reducing it to a very low digital computer level?

Hopfield: To make progress, we must have operational definitions. I can't explain that "feeling of hope," but the operational side of hope is easier to describe. If you are in the operational state of "hungry," certain things remind you of food, which if you're not in that biochemical state won't. Hope will have to do with hormonal states influencing choices as will be true of hunger. Particular hormones or neuroactive substances will be more present at one [illegible] or another. If you learn in the presence of one, it will tend to make you remember those general structures when it is present once again. I think hope and hunger are related phenomena. I can't say why you feel hungry or hopeful or what those *feelings* are. But I can try to understand why you act under certain circumstances as though you are hungry or hopeful. That's operational. I can get into that.

Omni: Everything we feel can be reduced to engineering?

Hopfield: Some things described as feelings can be operationally reduced to engineering. But what we feel is difficult. Specific drugs are known to result in a feeling of pleasure. We even understand the molecular sites to which they bind. This does not answer the question, "What is pleasure?"

Omni: So future computers or robots may not show consciousness but will show some consequences of emotions? Perhaps awareness of emotions?

Hopfield: Nobody has dealt with artificial neural networks that make measurements of themselves. If a network could do that, it could have an internal dialogue about emotion because it will know something about its internal state.

Omni: Doesn't this ability to self-monitor potentially free computers from human control?

Hopfield: Computers already talk to themselves about their internal state. All machines these days do a self-check when you turn them on. They say, "I am okay, Jack!" after exercising their logic and memory. That's a beginning. They check themselves with procedures already out of the user's control. If you could have more of a dialogue with them, they might begin to tell you in what sense they don't feel well.

Omni: Won't emotions be complicated to build in?

Hopfield: Operationally, emotions would be relatively simple to construct. It's only self-dialogue that's hard. The present state of emotion in biology is very provocative. Depression, for instance, has biochemical symptoms. But that leaves totally unanswered the question of mechanisms by which depressing thoughts are caused by a chemical state. Nobody in biology really works on that. Marvelous topic.

Researchers working on ways of treating depression do it in the sense of the auto mechanic who tells you that a normal car has gasoline in it, and yours does not, and if gasoline is added, the car will probably work. When we fix this biochemistry, the sign of depression, it will probably go away. With the automobile, the mechanic is not addressing how the engine works, nor is the neuroscientist asking how the lack of a chemical gives rise to depressed thoughts. No one in clinical neurobiology asks what's the difference between exalting and depressing thoughts such that now you can have one and not the other—how the brain thinks.

Omni: What about the Japanese?

Hopfield: They are a real force in the field. They feel they have a language problem, that the world is not going to learn Japanese, and that they'd be at less of a disadvantage if they could speak Japanese at one end of a telephone and have English come out the other. And vice versa. They see artificial neural systems as an important approach to this problem.

Many of their electronics companies have small neural biology groups and are working on the same problems we are. The Japanese and Chinese are specifically working on software to recognize kanji, or written characters. There are two Japanese alphabets: phonetic and real pictographs. In one direction, they'd like a system to read writing, and in the other direction, to type. At present, it's slow to type with a thousand symbols, so they'd like to type phonetically and have these symbolic characters appear correctly in context.

Omni: What about military applications?

Hopfield: There's promise in aspects of pattern recognition for feature surveillance where millions of pictures are shot to monitor missiles in other countries. People are not going to look at all those photos. You want to select by fast pattern recognition the 1 percent most relevant.

Omni: Star Wars stuff?

Hopfield: There are much more exciting ways to spend technological money. Simple pattern recognition. Why should you have to pay attention on the freeway? You could probably teach your dog to drive adequately on the freeway under most circumstances. Why can't neural nets do the early part of the visual processing well enough so that a digital machine could finish it off—keep you on the road, not running into the car ahead of you, and staying in lane?

Omni: In computer chess, why not build the best players you can and get them to play each other and learn to become the best by playing hundreds of thousands of games?

Hopfield: In theory, you could do it if the networks were sufficiently complex. But then your game is tailored around your opponent's. I've heard about the problem in humans. Two brothers played only with each other and didn't develop chess as it's normally played. They both learned an abnormal, highly stylized game, and they could be clobbered by anybody playing normal chess.

Omni: Your father was always thinking physics, wasn't he?

Hopfield: One day I was with Father, rowing on a river with one of my older sisters. Her one-year-old child stood up in the back of the boat and fell out into the very muddy water. My sister screamed, and my father stood up but didn't move. She cried, "You're not doing anything!" He said, "Don't worry, she'll float." He waited until she came up into view before diving in. It was his immediate rational calculation that everything was going to be fine, and the operational thing to do was wait until the laws of physics came forward—because the child was fat!

Omni: Do you have that attitude?

Hopfield: Well, I'm afraid my family would say that I tend to be overly rational. There is always the question in life as to the balance between rational and emotional reactions. A totally rational outlook can be very unsatisfactory. Life needs poetry. ∞

SACRED

CONTINUED FROM PAGE 64

ing. "That one, Jackie. That one is special, yaar. It's a smasheroo, Jackie. An ultrahit! Bloody champagne and flower garlands here, Jackie boy. It's big. Mega."

"You liked the Moon, eh," Jackie said, stunned.

"Love the Moon. Love all that nonsense."

"I did hear about your brother's government appointment. Congratulations."

Goldie chuckled. "Bloody hell, Jackie. You're the fourth fellow today to make that silly mistake. That Vachchani fellow in aeronautics, he's not my brother. My brother's a bloody contractor; he builds bloody houses, Jackie. This other Vachchani, he's some scientist egghead fellow. That Moon stuff is stupid crazy, it will never happen." He laughed, then dropped his voice. "The fourth one is shit, Jackie. Women's weepies are a drug on the bloody market this season, you rascal. Send me something funny next time. A bloody dance comedy."

"Will do," Jackie said.

"This girl Betty," Goldie said. "She likes to work?"

"Yes."

"She's a party girl, too?"

"You might say so."

"I want to meet this Betty. You send her here on the very next train. No, an aeroplane, hang the cost. And that soundtrack man too. My kids love that damned ugly music. If the kids love it, there's money in it."

"I need them both, Goldie. For my next feature. Got them under contract, yaar."

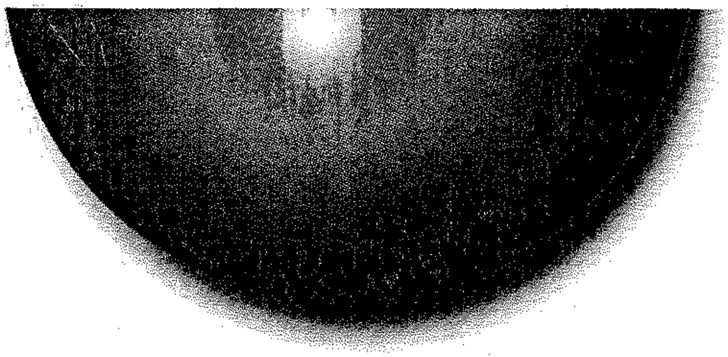
Goldie paused. Jackie waited him out.

"You got a little tax trouble, Jackie? I'm going to see to fixing that silly business, yaar. See to that straightaway. Personally."

Jackie let out a breath. "They're as good as on the way, Goldieji."

"You got it then. You're a funny fellow, Jackie." There was a digital clatter as the phone went dead.

The studio lights of the Japanese crew flashed on, framing Jackie in the graveyard in a phosphorescent glare. "Bloody hell!" Jackie shouted, flinging the phone away into the air and clapping his hands. "Party, my crew! Big party tonight for every bloody soul, and the bill is on Jackie Amar!" He whooped aloud. "If you're not drunk and dancing tonight, then you're no friend of mine! My God, everybody! My God, but life is good." ∞



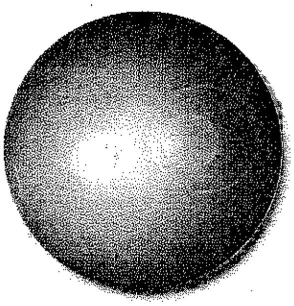
As silicon chips are pushed closer to their technological limits, engineers are moving to the molecular level to deliver the next step in computing speed.

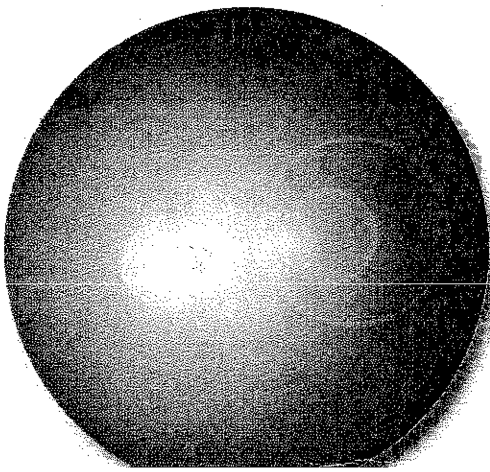
Quantum Leap

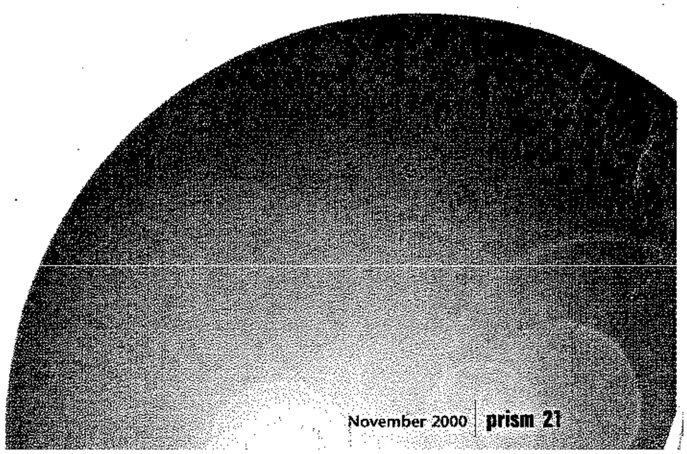
By Corinna Wu

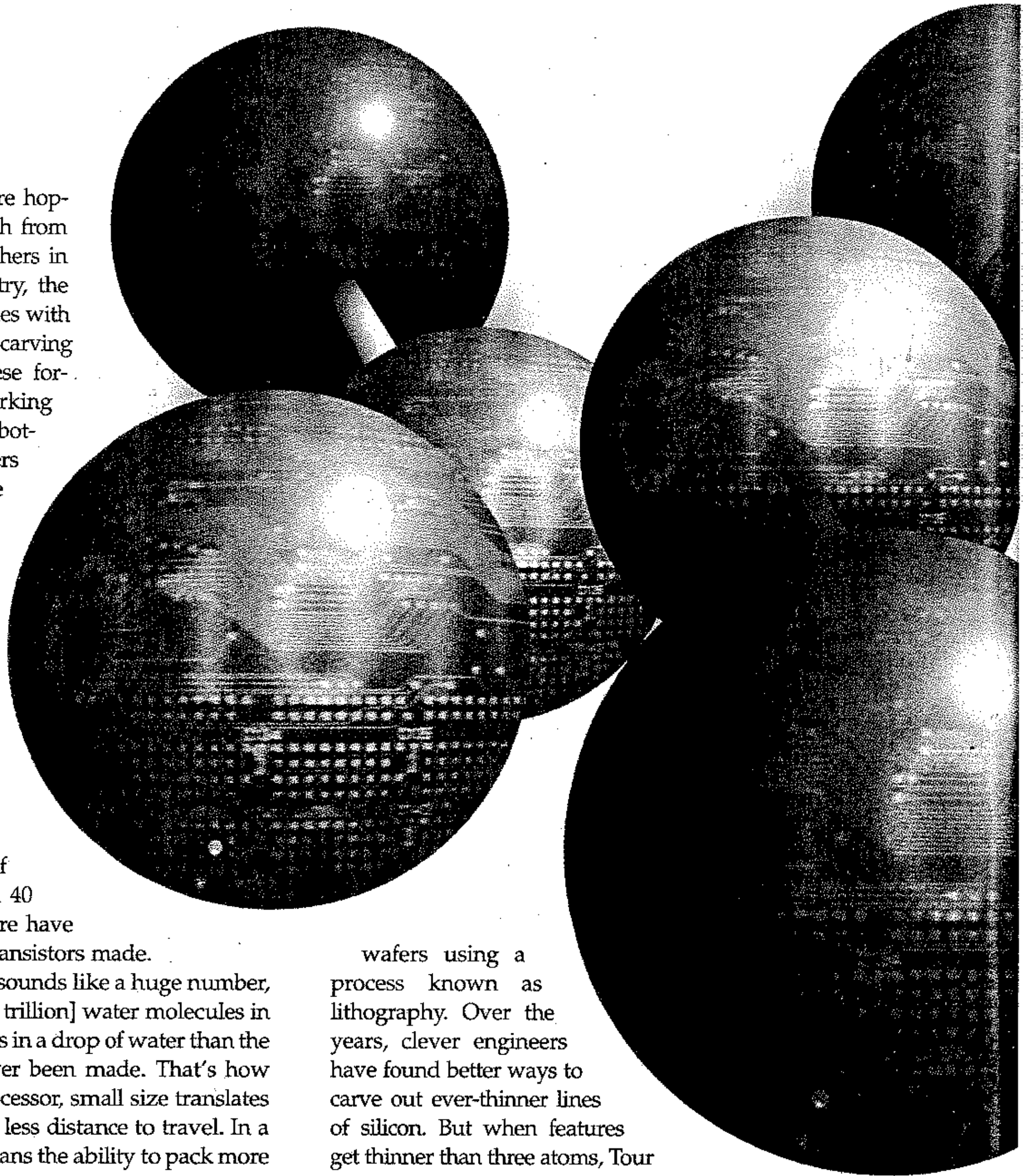
In years past, old folks would gather their grandkids around their feet and spin tales of hardship that inevitably involved having to walk two miles to school uphill in the snow—both ways. Children of today, living in the information age, might one day do the same to their grandkids, recalling endless download times with 56K modems and computers that ran at only 500 megahertz.

It's apparent that silicon technology, the basis of modern computing, has changed society immeasurably over the last half century. In 1965, Gordon Moore, cofounder of Intel, quantified that pace of change. He said that the density of transistors on integrated circuits doubles every 18 months or so, and the speed and power of those chips follows suit. So far, this axiom has held true. Over the years, engineers have repeatedly come up with better ways to pack a greater number of transistors into smaller spaces.









Now, scientists and engineers are hoping to keep this exponential growth from slowing to a halt. To many researchers in academia, government, and industry, the key to fulfilling Moore's prophecy lies with molecular electronics. Instead of carving computer chips out of silicon, these forward-thinking scientists are working toward building devices from the bottom up out of molecules. Researchers say that these molecules—which are generally elongated organic molecules with electronic properties that allow electrons to flow from one end to the other—can replicate the function of transistors and other elements that carry electric current and store information. Devices based on molecular electronics promise to be not only more powerful but significantly cheaper.

Chemist James Tour of Rice University explains the potential of molecular electronics this way: "In 40 years of silicon manufacturing, there have been less than [10 million trillion] transistors made. No more than that." Although that sounds like a huge number, "one drop of water has [100 million trillion] water molecules in it. So there's 10 times more molecules in a drop of water than the number of transistors that have ever been made. That's how small molecules are." In a microprocessor, small size translates into speed, since the electrons have less distance to travel. In a computer memory device, small means the ability to pack more information into the same space, boosting storage capacity.

These futuristic dreams have been grounded by some very real and promising results, and the hard work is starting to pay off, says Mark Reed, head of the electrical engineering department at Yale University. "It has me very excited. Like any technology that's disruptive, it's going to do things we haven't thought of yet." Tour predicts that in 10 years, there will be a working molecular computer. Hybrid systems that integrate with existing technology will appear even sooner—in 3 to 5 years.

Reinventing the Chip

Not long ago, the words "molecular" and "electronics" were rarely mentioned together. Silicon ruled—and still does rule—the world of electronics. But the shiny, silver-colored semiconductor is rapidly reaching its physical and practical limits. It takes roughly $2.5 billion to build a traditional chip fabrication line, says Tour. The amount of money needed to design and manufacture faster chips "gets beyond even what a consortium can do," he says. Silicon Valley may be awash in money, but even its deep pockets won't be able to leap the technological hurdles in current chip technology.

The reason behind this barrier is that "silicon is a top-down technology," Tour explains. Transistors are etched into thin silicon wafers using a process known as lithography. Over the years, clever engineers have found better ways to carve out ever-thinner lines of silicon. But when features get thinner than three atoms, Tour says, the tiny electric currents coursing through the material start to leak out. Silicon acts as a semiconductor because electrons run through a broad swath of allowed energies known as bands. "When you build a structure too small, the bands start going away," he says. "It's a fundamental scientific barrier, not a technological barrier. Those can always be blown through by good engineers." It's possible to carve out lines of individual silicon atoms, but they won't do anything useful.

Also, at that size, quantum effects become more important, making the behavior of electrons less predictable. "If transistors become too small, current can no longer be controlled," says Herb Goronkin, vice president and director of the Physical Research Laboratory at Motorola in Tempe, Ariz. Molecules, on the other hand, don't rely on bands to conduct electrons. Instead, their electrons possess discrete energies—like rungs on a ladder—and can leap from one to the other. Molecules hang on tightly to electrons, keeping information from going astray.

Current manufacturing technology can carve out lines of silicon just five or six atoms thick—uncomfortably close to the limit. Tour recalls a discussion he had in May with a group at Texas Instruments about the three-atom barrier, and how engineers will reach it by 2006 or 2008. "They laughed and said, 'we'll be there by 2003 or 2004.'" With this fast-approaching deadline, scientists knew they needed a wholesale reinvention of the technology.

History Lesson

The progress in molecular electronics has paralleled that of solid-state electronics, says Ari Aviram of the IBM Watson Research Center in Yorktown Heights, N.Y. The first modern electronic components were diodes or rectifiers—devices that allow one-way flow of current. Home radio kits popular in the early 20th century, for example, were based on diodes made of crystals. Then came triodes—vacuum tubes that had three electrodes inside. One of the electrodes determined how much current flowed between the other two. "A very small current in the center one could control the current between the anode and cathode," Aviram explains. And vacuum tubes, of course, ran the earliest computers.

In 1948, Walter Brattain and James Bardeen built the first transistor, which essentially turned the vacuum tube into a solid-state device. It was a funny-looking contraption—a plastic triangle covered with a piece of gold foil, suspended by a spring, and lightly touching a hunk of germanium. By 1954, Texas Instruments had begun mass-producing transistors made out of silicon. Researchers soon began developing ways to connect many such transistors on a single piece of material. These integrated chips, which are smaller than a thumbnail yet contain millions of transistors, power the computers we know today. Now, the challenge for scientists interested in molecular electronics "is to translate from the solid state to a molecular world," says Aviram.

And researchers have begun to do just that. Like the early electronics pioneers, their first goal was to create a diode out of a single molecule. In 1974, Aviram and Mark Ratner of Northwestern University published a paper proposing the idea of a molecular rectifier, a molecule that conducts current in one direction. Many scientists in the field trace the origins of molecular electronics back to that event.

It took more than two decades to translate their vision into reality. It wasn't until the 1980s, when nanotechnology became the hot new field, that researchers realized the value in thinking small—and had the tools to achieve their goals. One such tool was the scanning tunneling microscope, or STM, which allowed researchers to visualize and manipulate individual atoms. In 1996, Reed and his coworkers used an STM to measure the electric current flowing across a single molecule.

The amount was impressive. The molecule they tested could transmit a million million electrons per second, even more than theoretically predicted. Soon, other groups showed

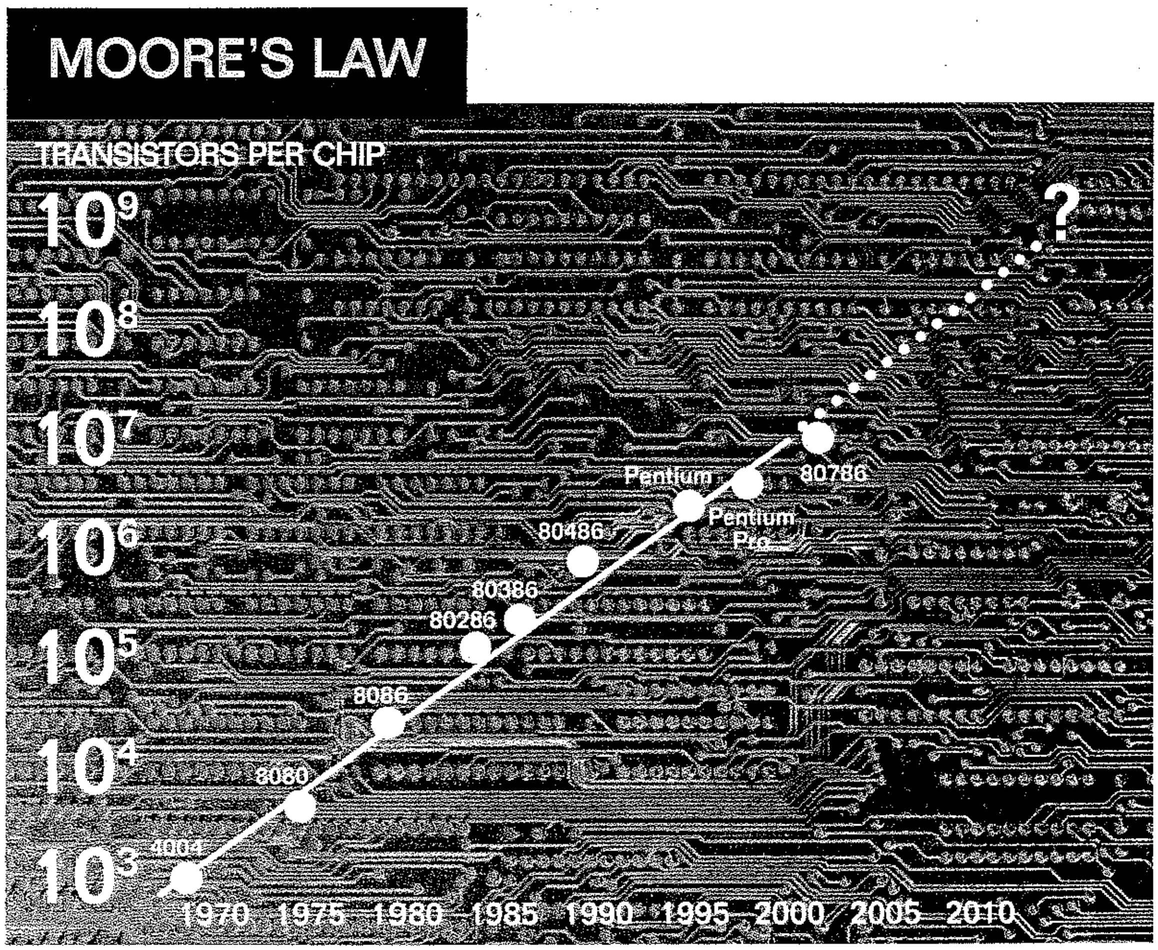


Chart is based on data from Quantum Structures Research Initiative that solid-state devices could indeed be miniaturized into molecules. The first results came from scientists at the University of Exeter in England. They sandwiched molecules between two metal electrodes and observed current flow in a single direction. But Aviram says the results raised some controversy because the two metals were different. No one could be sure that the rectifying effect didn't result from the potential difference between the different metals.

Then in 1997, Robert Metzger of the University of Alabama in Tuscaloosa put those doubts to rest. He and his group successfully synthesized a molecule that channeled current in one direction even when it was sandwiched between two electrodes made of the same metal. Since then, advancements in the field have come one on top of another. "This has gone at a speed that's just unprecedented," says Reed. "It's absolutely astounding. Of course, the venture capitalists want to know why it's taking so long!"

Now, researchers are starting to build more complicated and practical devices. "This field got a shot in the arm when the UCLA group and ours published results last year," says Reed. "People sat up and said, 'We can really make things.'"

In July 1999, James Heath and Fraser Stoddart of UCLA announced they had built a switch out of molecules called rotaxanes. Rotaxanes look something like a ring threaded on a dumbbell. The ring-shaped portion can slide back and forth, shuttling between bulky chemical groups on the ends of the dumbbell component. The UCLA researchers sandwiched a thin layer of rotaxanes between two electrodes and showed that the device could act as a switch. Then, by connecting several of these switches together, they fabricated logic gates, which form the fundamental architecture of a computer chip.

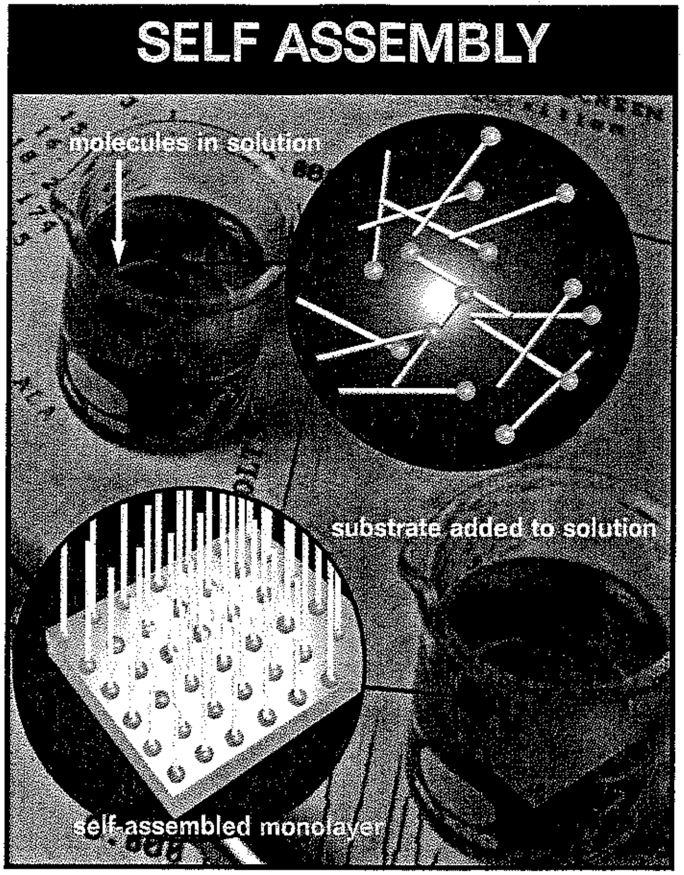
A few months later, Reed, Tour, and their colleagues described another molecular switch consisting of a thin layer of molecules sandwiched between two contacts. By varying the potential placed across the molecules, the scientists could turn the current flow on or off. These molecules "beat the pants off of silicon today," says Tour. A silicon switch exhibits a 5 to 1 ratio between the strengths of the on and off states, where a higher ratio means less chance for confusion between when the switch is on or off, thus reducing error. In the molecular switch, the ratio is 1,000 to 1.

Then, close on the heels of that achievement, Reed and Tour's group announced the creation of a circuit element that could be used in computer memory. The dynamic random access memory, or DRAM, in today's computers has to be refreshed 100,000 times a second, says Tour. "Our memory lasts 10 minutes. It's stable over that time." Less refreshing means that it consumes less power.

Charles Lieber of Harvard University and his group have also created their own version of a stable memory device. It consists of a grid of nanotubes, tiny hollow tubes of pure carbon that can conduct electricity. Each point where the nanotubes cross each other can register an on or off state, determined by how far apart the overlapping tubes are. The device works as nonvolatile random access memory, meaning "what-

HOW THEY STACK UP

	Silicon	Molecular Electronics
SPEED	1.5 GHz	Much faster
SIZE OF KEY FEATURES	180 nanometers	A few nanometers
NUMBER OF TRANSISTORS ON CHIP	28 million	Billions, maybe trillions
COST OF FABRICATION FACILITY	$200 billion by 2015	Perhaps 1/10 that cost
DRAM ELECTRON TRAPPING TIME	A few milliseconds	10 minutes



ever information you write stays there," Lieber says.

He adds that nanotubes are natural candidates as molecular wires, which will be necessary for connecting nanoscopic devices together. "This is critical. You can't just have one or two devices. You have to wire these things up." Nanotubes are "the closest thing to a hybrid between a real molecule—that can be synthesized to a precise structure and can extend for large distances—and the solid-state."

Big Questions, Big Rewards

With devices like diodes and switches in hand, researchers are turning their attention to the multimillion-dollar prize: molecular transistors. "The rectifier was important in showing that molecules can be electronic components," says Aviram, but the transistor is the component that makes the core of any electronics. "You can build any computer out of it." Tour has synthesized several molecules that fit the profile of a molecular transistor. The tiny size of molecules makes testing a molecular transistor difficult, however. Finding a way to string a molecule between two electrodes was hard enough—"we beat our heads for five years on this problem," says Reed—but a transistor has three contacts instead of the diode's two. Somehow, Tour has to find a way to touch a third electrode to the molecule. "We have whopping big leads," he says. "It's pretty hard to bring in a third lead."

While researchers in molecular electronics struggle with technical challenges, they are also thinking about what to do with all these elements once they've built them. "The question is, how do you rig these things up?" says Tour.

The answer is to let the molecules rig themselves up, a process known as self-assembly. Chemists can design molecules that have a natural affinity for each other. Put those molecules in solution, and they will seek each other out. For example, gold is strongly attracted to sulfur groups. By placing sulfur in strategic places in a molecule, scientists can design the molecule to grab onto a gold electrode or wire.

"One thing that gets overlooked is that [self-assembly] offers a much simpler way of making devices," says Aviram. Making a conventional memory device requires about 500 different steps to carve out patterns in silicon. In molecular devices, lithography could be used just to lay down a pattern of metal interconnects. Then, the chip could simply be dipped into a solution of molecules, which would arrange themselves in the proper places. A manufacturing process like this could decrease the cost of manufacturing a chip to one-tenth of what it is now, Aviram estimates.

Patterns can be written onto surfaces other ways too. Chad Mirkin of Northwestern University and his colleagues have developed a technique they call dip-pen nanolithography. The researchers use the sharp tip of an atomic force microscope to deposit narrow lines of molecules on a surface. The technique works much like the old fountain pens of yesteryear, with the microscope serving as the pen nib, the solid surface as paper, and the molecules as ink.

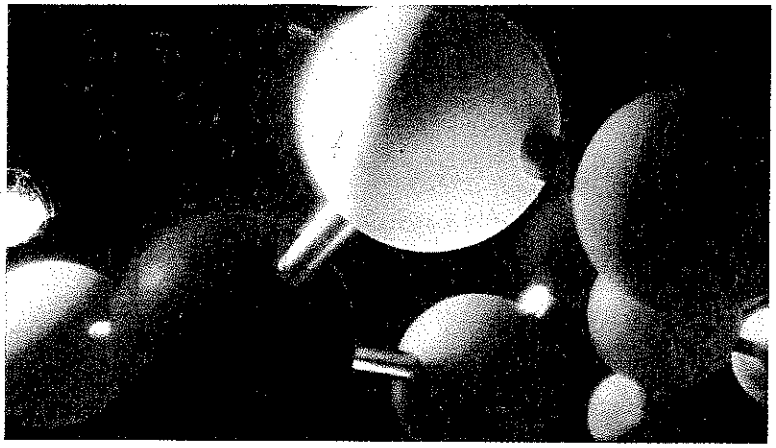
Recently, Mirkin and his group created a "nanoplotter," which writes with eight pens at the same time, and plan to increase the number to 32. Using software, the researchers can program the nanoplotter to write patterns automatically. "It's going to be a tremendous discovery tool," says Mirkin, since it allows researchers to generate lots of different patterns in a short time.

Silicon's Staying Power

Although molecular electronics researchers are gung-ho about the possibilities of the field, none say that silicon is on its way out. "Silicon does a number of things very well," Reed emphasizes. "We don't want to spit into the wind." He and others in the field say that molecular electronics will complement and enhance silicon technology. With this in mind, they have to face yet another big question: how to integrate a molecular device into all the silicon ones existing today. In other words, "How do you connect that beaker to the wall?" asks Bill Warren of the Defense Advanced Research Projects Agency in Arlington, Va., who funds several molecular electronics projects.

Ideally, scientists want to be able to "pull out a chip from a PC and stick another in," says Tour. But as they've learned from their work with molecular transistors, there's a problem with connecting big electrodes to these tiny molecules. Tour says that molecular electronics is fraught with problems, "but so was silicon." The extraordinary success of silicon technology gives these researchers confidence that molecular electronics will follow a similar soaring trajectory.

Another vote of confidence comes from companies that have built their fortunes on silicon. "Silicon will continue to grow and continue to be needed," says Motorola's Goronkin, but "we recognize that conventional silicon technology encounters sizes at which quantum effects become observable. That results in degraded performance." That has prompted Motorola,



Hewlett-Packard, and other companies to form partnerships with academics to explore molecule-based technologies.

Reed, Tour, and others formed a company in November 1999 called Molecular Electronics Corp. to "go ahead and try to commercialize some of these things," says Tour. Reed says investors are pouring money into it—perhaps the surest sign of acceptance that a new idea gets in today's economy.

Unlimited Possibilities

The field of molecular electronics is still young, so no one knows what full-function molecular devices will look like. The first devices will probably use groups of molecules rather than individual ones as elements, says Aviram. Complexity in function will be achieved by connecting these elements in creative ways, he adds.

And there's still a lot to learn about how these tiny devices behave. "Everyone needs to demonstrate that these devices can act in a stable, predictable manner," says Lieber. With some molecules, researchers need to exhibit an extraordinary amount of control. For example, the particular arrangement of carbon atoms in a nanotube affects its ability to conduct current. "It's not clear how anyone's going to control that," Lieber says. Other unknowns have to do with architecture—the basic manner in which computer elements are organized and integrated. "The architecture for silicon might not be appropriate for molecular electronics," says Goronkin.

But if scientists and engineers can surmount these hurdles, the world may see applications that once existed only in dreams. "If these devices are cheap, small, and even moderately powerful, you have the basis of a body-borne device," says Lieber. "You could have a postage-stamp-sized thing and not have to lug around a laptop."

And Reed is not only excited about what molecular electronics means from a scientific standpoint. He also thinks it could revolutionize thinking among educators. "It's not a traditional area," he says. "You're not going to find it as a subset in any engineering curriculum. Once you do, the field will be mature. What we have to do—our job as educators is—we need to enthuse students to these new, groundbreaking areas. We can say you don't have to follow in the steps of the old fogeys."

Even though these researchers hope to marry molecules and computers in their lifetime, they know that it will be up to future generations to nurture the relationship.

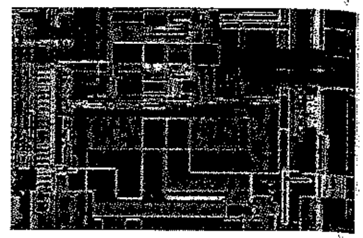
Corinna Wu is a freelance writer living in suburban Washington, D.C.

GLOSSARY

Silicon: A silvery-colored semiconductor material used in today's integrated circuit technology.

Transistor: An electronic device that controls current flow and serves as the basic element of a computer chip. Consists of three terminals: a source, a gate, and a drain. Applying a voltage to the gate controls current flow between the source and the drain.

Integrated chip: An electrical circuit consisting of millions of transistors, wires, and other devices built onto a centimeter-square piece of silicon.



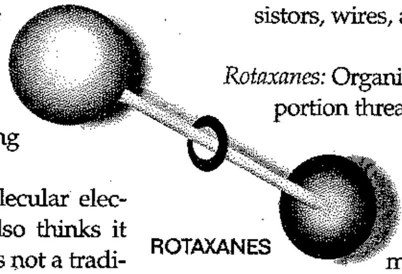
INTEGRATED CHIP

Moore's Law: A tenet that says the density of transistors on integrated circuits—and, therefore, the speed of the chips—doubles roughly every 18 months.

Photolithography: A method for constructing integrated chips, layer by layer. A silicon chip is coated with a chemical called a photoresist. Flashing a pattern of light and dark onto the photoresist causes it to harden in the areas exposed to light. The parts not exposed to light stay soft and are etched away. The process is repeated to deposit subsequent layers of material onto the chip. A photolithographic manufacturing process can take hundreds of separate steps, but hundreds of chips are built onto a single silicon wafer at the same time.

Molecular electronics: A new approach to making integrated chips using organic molecules instead of silicon as transistors, wires, and other electronic devices.

Rotaxanes: Organic molecules that consist of a ring-shaped portion threaded on a dumbbell-shaped component. Can act as molecular switches as the ring slides back and forth.

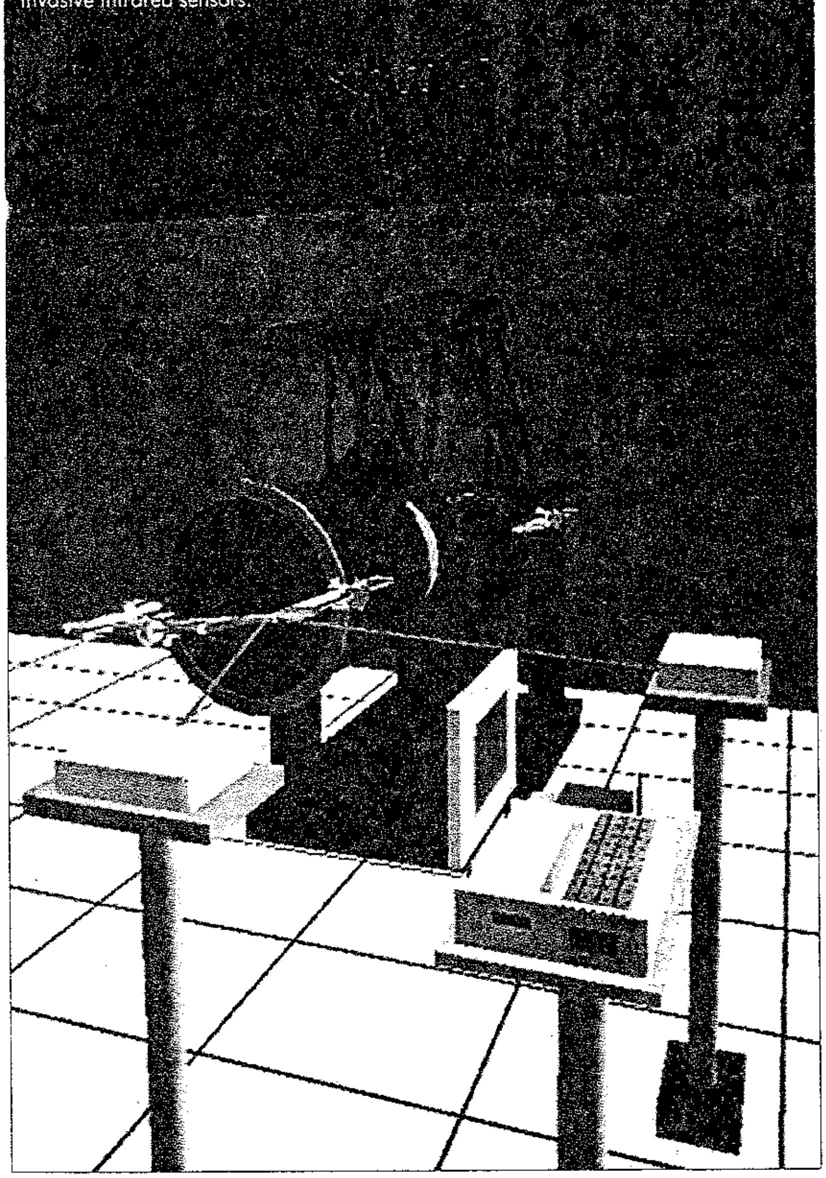


ROTAXANES

Carbon nanotubes: Tiny, hollow tubes made of pure carbon just a few nanometers in diameter. Nanotubes can conduct electricity and may be useful as wires for connecting molecular devices together.

Self-assembly: A process for putting together molecular devices that relies on a molecule's natural attraction for a material or other molecules. Molecules designed to have certain chemical groups will connect themselves together without need for human control.

A hard look at


An efficient method has been developed for balancing the Kuiper/Sofia Airborne Observatory Telescope employing neurocontroller and noninvasive infrared sensors.

Economic stresses are forcing many industries to reduce cost and time to market, and to insert emerging technologies into their products. Engineers are asked to design faster, ever more complex systems. They must find globally optimal designs that take uncertainties and risk into consideration. Conventional computational and design methods are inadequate to handle these tasks. Therefore, intense effort has been devoted in recent years to a new technology with high potential for solving complex problems with system uncertainties—computational intelligence and its associated tools, also called soft computing (SC).

Soft computing, a term introduced by Lotfi Zadeh of the University of California, Berkeley, describes several novel modes of computation that exploit tolerance for imprecision and uncertainty in real-world problems to achieve tractability, robustness, and low cost. SC has high potential for solving complex problems with system uncertainties. Its driver is the principle of complexity: As the complexity of an engineering system increases, our ability to predict its response diminishes, until a threshold is reached beyond which precision and relevance become almost mutually exclusive.

Consider, for example, numerical simulations in which sophisticated computational models are used for predicting the response, performance, and reliability of engineering systems, but the system parameters are little more than guesses. Such simulations can be characterized as correct but irrelevant computations—that is, forcing precision where it is not possible.

The principal constituents of SC are neurocomputing, fuzzy logic, and genetic algorithms.

soft computing

From neural networks to fuzzy logic and genetic algorithms, new computational modes are enabling faster design solutions, lower costs, and shorter time to market for aerospace products

by **Ahmed K. Noor,** Firman W. Perry professor of aerospace structures and applied mechanics, University of Virginia, and director, Center for Advanced Computational Technology, NASA-Langley; and **Charles C. Jorgensen,** senior scientist, Computational Sciences Div., Neural Engineering Laboratory, NASA-Ames

Neurocomputing

Neurocomputing is rooted in various disciplines, but the concept of artificial neural networks was inspired by biological networks. Neural networks are pattern computers—information processing devices (either algorithms or actual hardware). They use simplified mathematical functions to approximate the behavior of neurons in the brain. Biological neurons, as the structural constituents of the brain, are much slower than silicon logic gates. However, inferencing in biological neural networks is faster than the fastest computer. The brain compensates for the relatively slower chemical operation by having an enormous number of massively interconnected neurons.

These networks can be classified into biologically accurate (BA) and engineering-oriented (EO) approaches. Both are nonlinear, highly parallel models characterized by robustness and fault tolerance. They can also perform the following three functions:

- Learn by adapting synaptic weights to changes in the surrounding environment
- Handle imprecise, fuzzy, noisy, and probabalistic information
- Generalize from known tasks, or examples, to unknown ones.

BA and EO are attempts to mimic some, or all, of the characteristics of real cells. EO networks can be divided into artificial and computational neural networks (ANN and CNN). CNN attempts to replicate the computational power (low-level processing ability) of the BA. ANN endows machines with some of BA's higher level cognitive abilities.

The computational paradigm of BA and EO differs from a programmed instruction sequence in that information is stored in the synaptic connections. Each neuron is an elementary, or virtual, processor with primitive operations, such as summing weighted inputs and then amplifying or thresholding the sum.

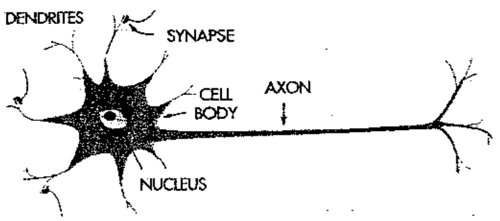
The three principal constituents of neural networks are:

- Topology—describing the number and characteristics of processing elements, the organization of the network into layers, and the connections between layers
- Learning—illustrating how the information is stored in the network and the training procedures
- Recall—describing the method of retrieving the stored information from the network (such as type of input/output values).

Each processing element (PE) relies on local information and acts independently of all others. The large number of connections, in the form of unidirectional communication channels between PEs, provides redundancy and facilitates a distributed representation.

Operations performed by neural networks include classification, pattern matching, optimization, control, and noise removal. Neural networks are used in many engineering applications as modeling and optimization tools. They are particularly useful in situations where good analytic models are either unknown or extremely complex. When analytic models are missing or incomplete, neural nets can be used to estimate a model from empirical data. They essentially work as interpolators: Using partial input/output data about a system, a

A BIOLOGICAL NEURON



neural net can be trained on new data to estimate other output values. When good analytic models are available, neural networks are likely to be less accurate than numerical solution techniques.

Neural networks can also be treated as weighted directed graphs in which artificial neurons are nodes and directed edges (with weights) are connections between neuron outputs and neuron inputs. Several types of neural net families are available, including self-organizing topologies, resonance models, coupled oscillators, and stochastic models. Based on the connection pattern (architecture), neural nets can be grouped into feed-forward and recurrent (or feedback) networks. Also, neurohardware has been developed that incorporates embedded neuroalgorithms. Several high-performance, special-purpose digital, analog, and hybrid neuroarchitectures are now available.

Fuzzy logic

The second major component of soft computing is fuzzy logic. Introduced in 1965 by Zadeh, fuzzy logic provides a mathematical tool for dealing with uncertainty and imprecision. This is done by using mostly words in computing and reasoning as a way of implementing general concepts. More recently, Zadeh suggested that the main contribution of fuzzy logic is a methodology for computing with words. No other methodology serves this purpose.

Fuzzy logic aims at rapidly finding acceptable (not necessarily accurate) solutions by permitting quantification of information in linguistic form. It is based on various mathematical concepts, such as fuzzy sets, membership function, and possibility. Fuzzy sets are imprecisely defined sets, not having a crisp boundary. Unlike ordinary sets, fuzzy sets provide a gradual transition from "belonging" to "not belonging" to a set. This is described by a membership function, which takes on values in the interval 0,1. The concept of possibility provides a mechanism for interpreting factual statements involving fuzzy sets.

The solution of practical problems using fuzzy models can be divided into three phases: In the first phase, the real system parameters are converted into labeled linguistic parameters (such as small, medium, and large), a process called fuzzification.

The second phase, analysis, involves using if-then rules to relate the inputs to the outputs; membership functions for inputs and outputs; and a procedure to combine fuzzy sets and rules to produce results.

The third phase consists of converting output system characteristics from linguistic output to real parameters (defuzzification).

The methodology can be described as follows: Given an unsolvable problem in real space, enlarge the space and look for the solution in the superset. Then specialize the solution to the original real constraints.

Fuzzy logic can be implemented by using table lookup, software, or fuzzy coprocessors. A wide variety of commercial software and hardware tools are available for facilitating the deployment of industrial fuzzy logic control applications.

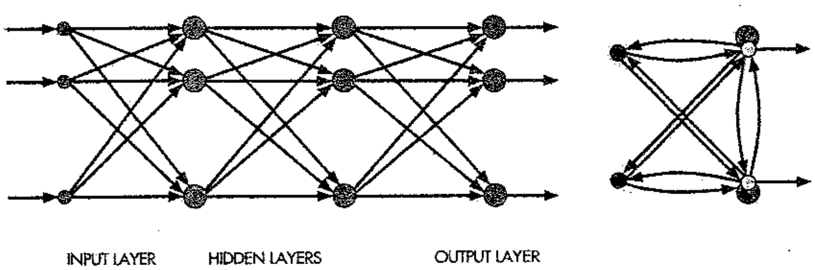
Genetic algorithms

Genetic algorithms are biologically inspired evolutionary processes. They provide an adaptive, robust, parallel, and randomized searching technique in which a population of solutions evolves over a sequence of generations into a globally optimal solution.

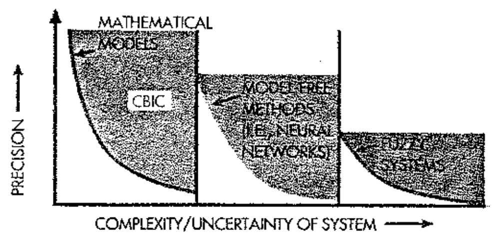
Typically, all solutions are represented by binary strings. Each trial solution is coded as a vector called a chromosome, with elements described as genes, and varying values at specific positions called alleles. Based on a fitness function, good solutions are selected for reproduction using genetic recombination operators such as crossover and mutation.

Genetic algorithms have heuristic strate-

FEED FORWARD AND RECURRENT/FEEDBACK NEURAL NETWORKS



PRINCIPLE OF COMPLEXITY



gies to help escape from local minima. The power of genetic algorithms derives largely from their global parallelism—the simultaneous allocation of search effort to many regions of the search area. They are best suited for complex, poorly understood problems with longer available computation time.

Hybrid systems

Judicious integration of the major components of SC can result in systems that are better in terms of parallelism, fault tolerance, adaptivity, and uncertainty management. Hybrid systems can make automated adaptive systems a reality in many applications. The reasoning power of fuzzy systems, when integrated with the learning capabilities of neural networks and genetic algorithms, has led to new commercial products and processes that are reasonably effective cognitive systems (systems that can learn and reason).

Artificial and computational intelligence

The definition of the term "intelligence" caused much debate among experts in many disciplines. A functional engineering definition of intelligence is the capability of a system to adapt its behavior to meet its goals in a range of environments. By this definition, intelligence is not a unique human quality—machines can be equipped with intelligent facilities. Attempts are being made to develop metrics for measuring a "machine intelligence quotient."

The notions of computational, artificial, and biological intelligence can be characterized in terms of the relationship among neural networks, pattern recognition, and intelligence. CI is a low-level cognition in the style of the mind. The distinction between expert systems (the most mature and resilient product of AI), fuzzy logic, neural nets, and conventional computational methods can be illustrated by the extent to which they use nonnumeric (symbolic) and numeric computations.

Soft computing has been used in the design and development of a wide variety of engineering products, including intelligent consumer goods, auto components, robots, and manufacturing equipment. The sample applications that follow represent developments at both NASA and aerospace companies.

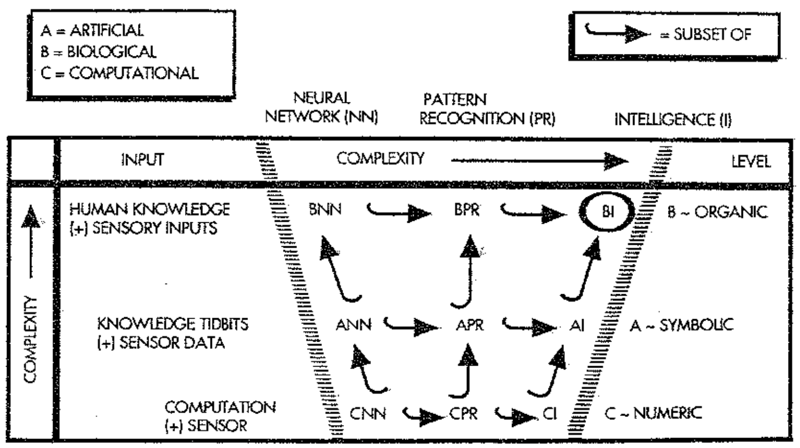
Neurocontrollers

Neurocontrol is especially suited for processes in which the analytic model, a requirement of conventional control methods, is either unavailable or highly nonlinear. It is based on system identification using input/output relations followed by adaptive control that learns through experience. Successful neurocontrol applications include robotics, automobiles (for cruise control or fuel injection), aircraft flight control and automatic landing systems, and computer performance tuning. Their success can be attributed in part to three factors: realization of fast control action; fast adaptation to variations in a large number of parameters; and possible robustness to variations in parameters not explicitly modeled.

Neural nets and wind tunnels

Neural networks increase productivity and lower costs in wind tunnel testing by learning to predict the performance of the new aircraft models being tested. A significant amount of wind tunnel test time is spent measuring aerodynamic effects of a large number of geometric variations. Such tests

RELATIONSHIP BETWEEN ARTIFICIAL, BIOLOGICAL, AND COMPUTATIONAL INTELLIGENCE



Neurocontrol research projects at NASA

Among the research programs at NASA are these neurocontrol projects.

Intelligent flight control. Neural networks are used to identify critical stability and control properties during flight. Algorithms are developed for automatic synthesis of optimal controllers that maximize flight performance under simulated accident conditions, including soft sensor failures, loss of lifting surfaces, and actuator malfunctions or damage. This joint venture between Ames, Dryden, and McDonnell Douglas addresses the need for control software that can be developed faster and tested at lower cost, and for safer flight systems that can accommodate major changes in aircraft stability and control characteristics that could result from failures in flight control actuation or damage to aircraft control surfaces. Early software tests are under way on a specially modified F-15 aircraft. In 1997, neural controllers will be used to adjust to simulated accident conditions under piloted flight scenarios.

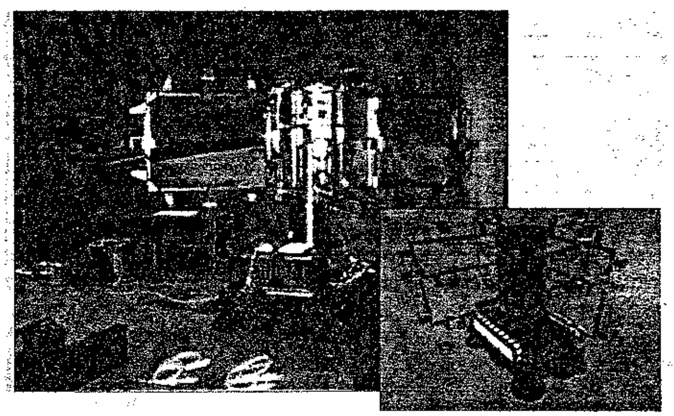
Propulsion-controlled aircraft. Catastrophic accidents have resulted from partial or total failures of conventional aircraft flight controls, or from in-flight structural damage that leaves only the engines operative. Such accidents may be preventable if sufficient flight control authority remains through application of jet engine propulsion control. The concept is to use such control to execute a safe emergency landing even though flight control surfaces may not be operational.

Neural-based control laws that can learn on-line changes in aircraft dynamics in real time have been demonstrated, as have output engine commands to regain flight control of a damaged jet. A combination of symmetric and asymmetric engine propulsion, rather than flight control surfaces, is used to provide the necessary forces and moments.

Very-high-fidelity piloted simulation tests (level D) were conducted for the propulsion-only control concept in the Advanced Concepts Flight Simulator at NASA-Ames in 1994. This year as part of the Dryden Flight Control Program propulsion-only control successfully landed an MD-11 aircraft under simulated total hydraulic failure. The method is now being considered for inclusion in the civilian air fleet pending approval and further testing by the FAA. Incorporation of improved neural net models of the aircraft engines is being developed for the Boeing 747.

Balancing (stabilization) of space station centrifuge. Controlling time-varying nonlinear hardware with an unknown structure is very challenging. One particularly difficult task involved the control of vibrations caused by the artificial gravity centrifuge on board the space station.

A neural-network-controlled automated mass balance system is under development to cancel centrifuge imbalances. Here, a hardware simulator floating on air bearings is simultaneously modeled in a virtual reality environment under control of a neural net. When a change in balance weight is commanded by the net, the graphic centrifuge balancing element is moved to a new location while a command is sent to perform the same operation on the actual hardware. This combined neural net/virtual reality system permits a new level of control and analysis during the space centrifuge hardware design.



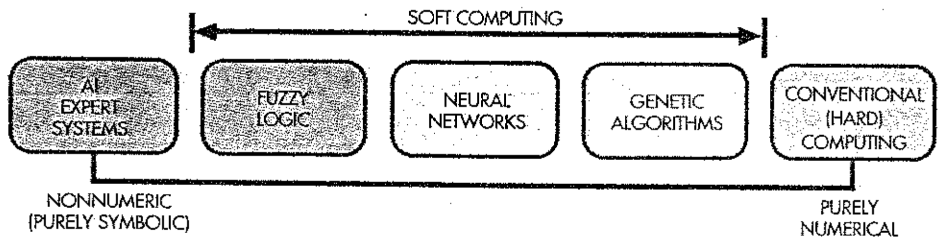
Hardware simulator and VR simluation are used for neural network testing of the space station centrifuge.

Balancing the Kuiper/Sofia Airborne Observatory Telescope. An efficient method has been developed for balancing the telescope employing neurocontroller and noninvasive infrared sensors. The method resulted in reducing both the time to balance the telescope before flight and operating cost.

Control of hypersonic waverider. A neural-based software controller was designed by Accurate Automation, under a NASA-Langley SBIR program, for use in the Low-Observable Flight Test Experiment hypersonic aircraft prototype, designed to operate between Mach 4 and 12. At this speed an aircraft is moving so fast it rides its own hypersonic shock wave (hence the name waverider). The neurocontroller learns to handle hypersonic aircraft performance by observing flight sensor inputs while noting an expert pilot's output responses. After learning to emulate human responses, the network continues to adapt by adjusting other variables such as speed to maximize fuel economy. Accurate Automation also has a specially designed neural network matched to adaptive software.

Information collected using neural nets to identify aircraft stability and control parameters is used to optimize damaged aircraft performance.

RELATIONSHIP BETWEEN AI EXPERT SYSTEMS, SOFT COMPUTING, AND HARD COMPUTING



can be extremely costly because of the high level of power needed to generate high-speed air movement ($3,000/hr for a large multimonth tunnel test, for example).

A neural net was trained to accurately predict the effects of the various parameters on lift, drag, side force, and pitching, yawing, and rolling moments, while using a much smaller subset of the test matrix than would normally be needed to generate an adequate database. Savings approaching 30% in test time, increased throughput, and associated costs were realized.

The method was recently used in tests of the Super High Alpha Research Concept (SHARC) aircraft. It proved to be very fast relative to computational approaches using complete mathematical simulation of flows —a model of an entire aircraft was learned in under 30 sec on a PC, to an accuracy well under 1% rms error. In tunnel tests of the SHARC, the learning of an adequate predictive model was achieved with approximately 40% less information. This reduction meant significantly lower facility operations costs due to less electricity, faster test turnaround, earlier identification of critical performance test areas, and improved analysis tools.

Neurofuzzy controllers for the Shuttle trainer

The goal of this project is to eliminate or minimize pilot-perceived differences between the Shuttle training aircraft (STA) response and the actual Shuttle controllers. The STA (a modified Gulfstream II) provides pilots with a realistic simulation of the Orbiter's atmospheric descent trajectory from 35,000 ft to simulated touchdown. This is achieved by controlling pitch, roll, and yaw, supplemented by direct lift control and in-flight reverse thrust, using an advanced digital avionics system.

New algorithms have been developed and demonstrated based on combined neurofuzzy techniques for automatic and adaptive refinement of the controller.

Planetary passage prediction

Neural networks and genetic algorithms are being used together to predict the presence of planets orbiting remote star systems. A neural-genetic filter is used to process variations in star light intensities as remote planetary bodies orbit their suns. When a body partially eclipses a sun's surface, periodic drops in luminosity occur at varying frequencies, depending on the orbit and the size of the planets.

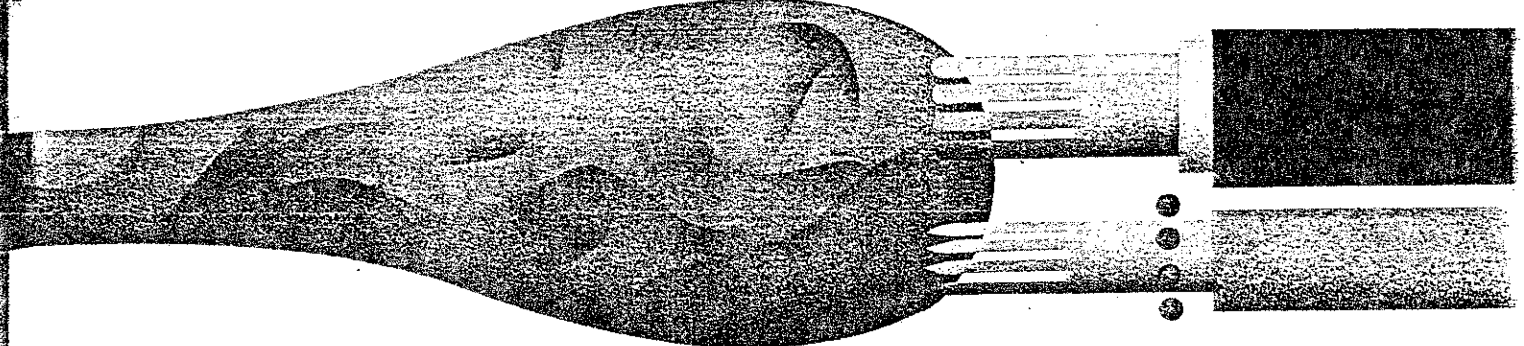
By learning filters tuned for certain frequencies, and using other available data about the size and distance of the sun, it is possible to detect large numbers of Earth-size bodies that could not be readily identified using current methods. Signal detection may require very subtle nonlinear filters to find the low-level signal-to-noise ratios based on predicted data. By using neural and genetic methods, many more potential filters can be explored.

Future directions

The coming decade will bring dramatic improvements in the software and hardware tools of SC, including the construction of optical neural chips and analog VLSI chips with thousands of neurons; development of hybrid neural network/fuzzy logic/genetic algorithm systems; and synergistic coupling of SC with other "intelligent" paradigms and facilities such as virtual reality.

Future applications will include complex dynamic systems such as jet engines, autonomous aircraft, and spacecraft. These feature high dimensionality of the decision space, large-grain uncertainty, poorly defined analytical models, multiplicity of performance objectives, nonlinearities, time delays, and disparate time scales. SC is likely to emerge as an essential technology for the conception, analysis, and design of these future aerospace systems. The impact of deploying this new technology will include reducing design and development times, and improving performance and reliability. ▲

A baby's brain is a work in progress, trillions of neurons waiting to be wired into a mind. The experiences of childhood, pioneering research shows, help form the brain's circuits—for music and math, language and emotion.



Your Child's Brain

BY SHARON BEGLEY

YOU HOLD YOUR NEWBORN SO HIS SKY-blue eyes are just inches from the brightly patterned wallpaper. *ZZZt:* a neuron from his retina makes an electrical connection with one in his brain's visual cortex. You gently touch his palm with a clothespin; he grasps it, drops it, and you return it to him with soft words and a smile. *Crackle:* neurons from his hand strengthen their connection to those in his sensory-motor cortex. He cries in the night; you feed him, holding his gaze because nature has seen to it that the distance from a parent's crooked elbow to his eyes exactly matches the distance at which a baby focuses. *Zap:* neurons in the brain's amygdala send pulses of electricity through the circuits that control emotion. You hold him on your lap and talk . . . and neurons from his ears start hard-wiring connections to the auditory cortex.

And you thought you were just playing with your kid.

When a baby comes into the world her brain is a jumble of neurons, all waiting to be woven into the

ILLUSTRATIONS BY TERRY ALLEN

intricate tapestry of the mind. Some of the neurons have already been hard-wired, by the genes in the fertilized egg, into circuits that command breathing or control heartbeat, regulate body temperature or produce reflexes. But trillions upon trillions more are like the Pentium chips in a computer before the factory preloads the software. They are pure and of almost infinite potential, unprogrammed circuits that might one day compose rap songs and do calculus, erupt in fury and melt in ecstasy. If the neurons are used, they become integrated into the circuitry of the brain by connecting to other neurons; if they are not used, they may die. It is the experiences of childhood, determining which neurons are used, that wire the circuits of the brain as surely as a programmer at a keyboard reconfigures the circuits in a computer. Which keys are typed—which experiences a child has—determines whether the child grows up to be intelligent or dull, fearful or self-assured, articulate or tongue-tied. Early experiences are so powerful, says pediatric neurobiologist Harry Chugani of Wayne State University, that "they can completely change the way a person turns out."

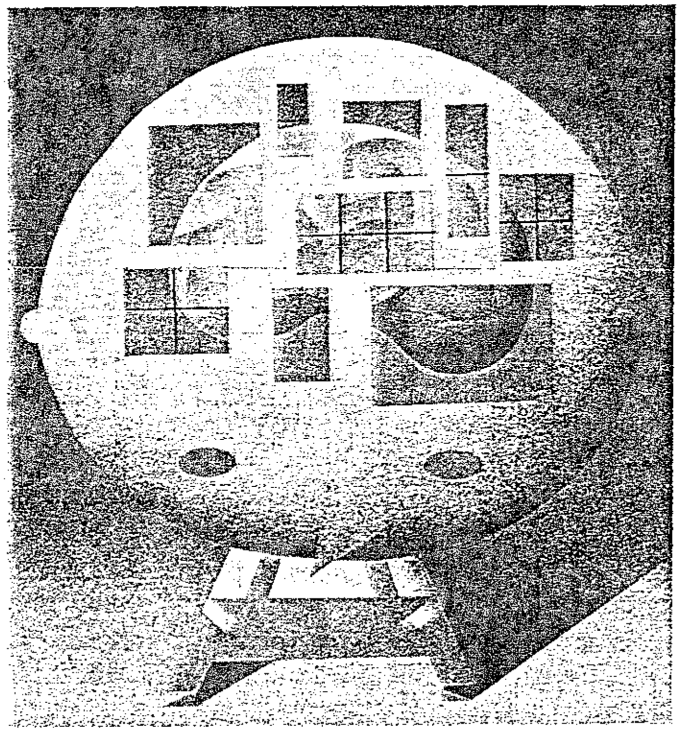
By adulthood the brain is crisscrossed with more than 100 billion neurons, each reaching out to thousands of others so that, all told, the brain has more than 100 trillion connections. It is those connections—more than the number of galaxies in the known universe—that give the brain its unrivaled powers. The traditional view was that the wiring diagram is predetermined, like one for a new house, by the genes in the fertilized egg. Unfortunately, even though half the genes—50,000—are involved in the central nervous system in some way, there are not enough of them to specify the brain's incomparably complex wiring. That leaves another possibility: genes might determine only the brain's main circuits, with something else shaping the trillions of finer connections. That something else is the environment, the myriad messages that the brain receives from the outside world. According to the emerging paradigm, "there are two broad stages of brain wiring," says developmental neurobiologist Carla Shatz of the University of California, Berkeley: "an early period, when experience is not required, and a later one, when it is."

Yet, once wired, there are limits to the brain's ability to create itself. Time limits. Called "critical periods," they are windows of opportunity that nature flings open, starting before birth, and then slams shut, one by one, with every additional candle on the child's birthday cake. In the experiments that gave birth to this paradigm in the 1970s, Torsten Wiesel and David Hubel found that sewing shut one eye of a newborn kitten rewired its brain: so few neurons connected from the shut eye to the visual cortex that the animal was blind even after its eye was reopened. Such rewiring did not occur in adult cats whose eyes were shut. Conclusion: there is a short, early period when circuits connect the retina to the visual cortex. When brain regions mature dictates how long they stay malleable. Sensory areas mature in early childhood; the emotional limbic system is wired by puberty; the frontal lobes—seat of understanding—develop at least through the age of 16.

The implications of this new understanding are at once promising and disturbing. They suggest that, with the right input at the right time, almost anything is possible. But they imply, too, that if you miss the window you're playing with a handicap. They offer an explanation of why the gains a toddler makes in Head Start are so often evanescent: this intensive instruction begins too late to fundamentally rewire the brain. And they make clear the mistake of postponing instruction in a second language (page 58). As Chugani asks, "What idiot decreed that foreign-language instruction not begin until high school?"

Neurobiologists are still at the dawn of understanding exactly which kinds of experiences, or sensory input, wire the brain in which ways. They know a great deal about the circuit for vision. It has a neuron-growth spurt at the age of 2 to 4 months, which corresponds to when babies start to really notice the world, and peaks at 8 months, when each neuron is connected to an astonishing 15,000 other neurons. A baby whose eyes are clouded by cataracts from birth will, despite cataract-removal surgery at the age of 2, be forever blind. For other systems, researchers know what happens, but not—at the level of neurons and molecules—how. They nevertheless remain confident that cognitive abilities work much like sensory ones, for the brain is parsimonious in how it conducts its affairs: a mechanism that works fine for wiring vision is not likely to be abandoned when it comes to circuits for music. "Connections are not forming willy-nilly," says Dale Purves of Duke University, "but are promoted by activity."

Language: Before there are words, in the world of a newborn, there are sounds. In English they are phonemes such as sharp ba's and da's, drawn-out ee's and ll's and sibilant sss's. In Japanese they are different—barked *hi*'s, merged rr/ll's. When a child hears a phoneme over and over, neurons from his ear stimulate the formation of



The Logical Brain

SKILL: Math and logic

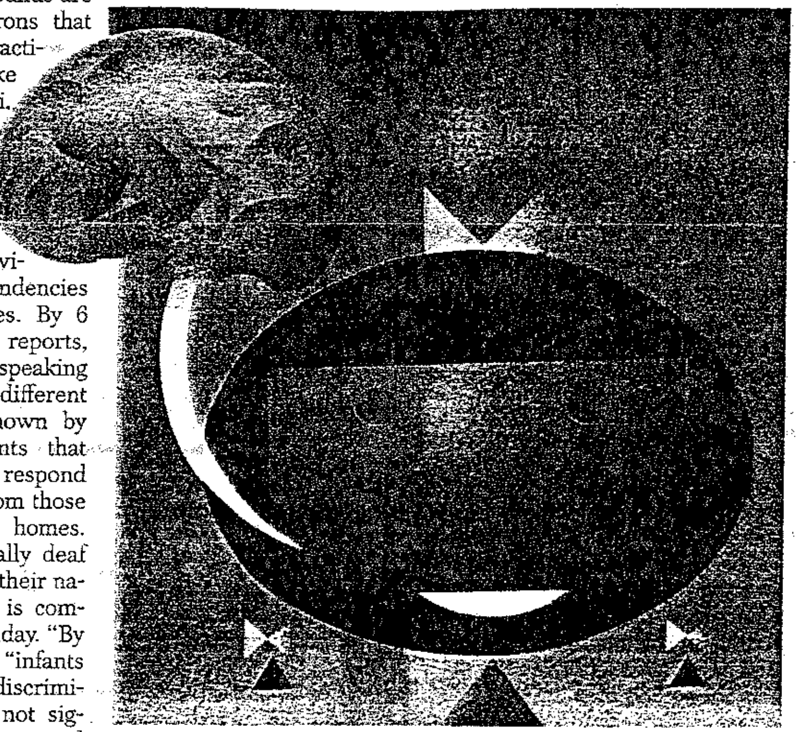
LEARNING WINDOW: Birth to 4 years

WHAT WE KNOW: Circuits for math reside in the brain's cortex, near those for music. Toddlers taught simple concepts, like one and many, do better in math. Music lessons may help develop spatial skills.

WHAT WE CAN DO ABOUT IT: Play counting games with a toddler. Have him set the table to learn one-to-one relationships—one plate, one fork per person. And, to hedge your bets, turn on a Mozart CD.

dedicated connections in his brain's auditory cortex. This "perceptual map," explains Patricia Kuhl of the University of Washington, reflects the apparent distance—and thus the similarity—between sounds. So in English-speakers, neurons in the auditory cortex that respond to "ra" lie far from those that respond to "la." But for Japanese, where the sounds are nearly identical, neurons that respond to "ra" are practically intertwined, like L.A. freeway spaghetti, with those for "la." As a result, a Japanese-speaker will have trouble distinguishing the two sounds.

Researchers find evidence of these tendencies across many languages. By 6 months of age, Kuhl reports, infants in English-speaking homes already have different auditory maps (as shown by electrical measurements that identify which neurons respond to different sounds) from those in Swedish-speaking homes. Children are functionally deaf to sounds absent from their native tongue. The map is completed by the first birthday. "By 12 months," says Kuhl, "infants have lost the ability to discriminate sounds that are not significant in their language, and their babbling has acquired the sound of their language."



The Language Brain

SKILL: Language

LEARNING WINDOW: Birth to 10 years

WHAT WE KNOW: Circuits in the auditory cortex, representing the sounds that form words, are wired by the age of 1. The more words a child hears by 2, the larger her vocabulary will grow. Hearing problems can impair the ability to match sounds to letters.

WHAT WE CAN DO ABOUT IT: Talk to your child—a lot. If you want her to master a second language, introduce it by the age of 10. Protect hearing by treating ear infections promptly.

Kuhl's findings help explain why learning a second language after, rather than with, the first is so difficult. "The perceptual map of the first language constrains the learning of a second," she says. In other words, the circuits are already wired for Spanish, and the remaining undedicated neurons have lost their ability to form basic new connections for, say, Greek. A child taught a second language after the age of 10 or so is unlikely ever to speak it like a native. Kuhl's work also suggests why related languages such as Spanish and French are easier to learn than unrelated ones: more of the existing circuits can do double duty.

With this basic circuitry established, a baby is primed to turn sounds into words. The more words a child hears, the faster she learns language, according to psychiatrist Janellen Huttenlocher of the University of Chicago. Infants whose mothers spoke to them a lot knew 131 more words at 20 months than did babies of more taciturn, or less involved, mothers; at 24 months, the gap had widened to 295 words. (Presumably the findings would also apply to a father if he were the primary caregiver.) It didn't matter which words the mother used—monosyllables seemed to work. The sound of words, it seems, builds up neural circuitry that can then absorb more words, much as creating a computer file allows the user to fill it with prose. "There is a huge vocabulary to be acquired," says Huttenlocher, "and it can only be acquired through repeated exposure to words."

Music: Last October researchers at the University of Konstanz in Germany reported that exposure to music rewires neural circuits. In the brains of nine string players examined with magnetic resonance imaging, the amount of somatosensory cortex dedicated to the thumb and fifth finger of the left hand—the fingering digits—was significantly larger than in nonplayers. How long the players practiced each day did not affect the cortical map. But the age at which they had been introduced to their muse did: the younger the child when she took up an instrument, the more cortex she devoted to playing it.

Like other circuits formed early in life, the ones for music endure. Wayne State's Chugani played the guitar as a child, then gave it up. A few years ago he started taking piano lessons with his young daughter. She learned easily, but he couldn't get his fingers to follow his wishes. Yet when Chugani recently picked up a guitar, he found to his delight that "the songs are still there," much like the muscle memory for riding a bicycle.

Math and logic: At UC Irvine, Gordon Shaw suspected that all higher-order thinking is characterized by similar patterns of neuron firing. "If you're working with little kids," says Shaw, "you're not going to teach them higher mathematics or chess. But they are interested in and can process music." So Shaw and Frances Rauscher gave 19 preschoolers piano or singing lessons. After eight months, the researchers found, the children "dramatically improved in spatial reasoning," compared with children given no music lessons, as shown in their ability to work mazes, draw geometric figures and copy patterns of two-color blocks. The mechanism behind the "Mozart effect" remains murky, but Shaw suspects that when children exercise cortical neurons by listening to classical music, they are also strengthening circuits used for mathematics. Music, says the UC team, "excites the inherent brain patterns and enhances their use in complex reasoning tasks."

Emotions: The trunk lines for the circuits controlling emotion are laid down before birth. Then parents take over. Perhaps the strongest influence is what psychiatrist Daniel Stern calls attunement—whether caregivers "play back a child's inner feelings." If a baby's squeal of delight at a puppy is met with a smile and hug, if her excitement at seeing a plane overhead is mirrored, circuits for these emotions are reinforced. Apparently, the brain uses the same pathways to generate an emotion as to respond to one. So if an emotion is reciprocated, the electrical and chemical signals that produced it are reinforced. But if emotions are repeatedly met with indifference or a clashing response—Baby is proud of building a skyscraper out of Mom's best pots, and Mom is terminally annoyed—those circuits become confused and fail to strengthen. The key here is "repeatedly": one dismissive harrumph will not scar a child for life. It's the pattern that counts, and it can be very powerful: in one of Stern's studies, a baby whose mother never matched her level of excitement became extremely passive, unable to feel excitement or joy.

Experience can also wire the brain's "calm down" circuit, as Daniel Goleman describes in his best-selling "Emotional Intelligence." One father gently soothes his crying infant, another drops him into his crib; one mother hugs the toddler who just skinned her knee, another screams "It's your own stupid fault!" The first responses are attuned to the child's distress; the others are wildly out of emotional sync. Between 10 and 18 months, a cluster of cells in the rational prefrontal cortex is busy hooking up to the emotion regions. The circuit seems to grow into a control switch, able to calm agitation by infusing reason into emotion. Perhaps parental soothing trains this circuit, strengthening the neural connections that form it, so that the child learns how to calm herself down. This all happens so early that the effects of nurture can be misperceived as innate nature.

Stress and constant threats also rewire emotion circuits. These circuits are centered on the amygdala, a little almond-shaped structure deep in the brain whose job is to scan incoming sights and sounds for emotional content. According to a wiring diagram worked out by Joseph LeDoux of New York University, impulses from eye and ear reach the amygdala before they get to the rational, thoughtful neocortex. If a sight, sound or experience has proved painful before—Dad's drunken arrival home was followed by a beating—then the amygdala floods the circuits with neurochemicals before the higher brain knows what's happening. The more often this pathway is used, the easier it is to trigger: the mere memory of Dad may induce fear. Since the circuits can stay excited for days, the brain remains on high alert. In this state, says neuroscientist Bruce Perry of Baylor College of Medicine, more circuits attend to nonverbal cues—facial expressions, angry noises—that warn of impending danger. As a result, the cortex falls behind in development and has trouble assimilating complex information such as language.

SCHOOLS

Why Do Schools Flunk Biology?

BY LYNNELL HANCOCK

BIOLOGY IS A STAPLE AT MOST American high schools. Yet when it comes to the biology of the students themselves—how their brains develop and retain knowledge—school officials would rather not pay attention to the lessons. Can first graders handle French? What time should school start? Should music be cut? Biologists have some important evidence to offer. But not only are they ignored, their findings are often turned upside down.

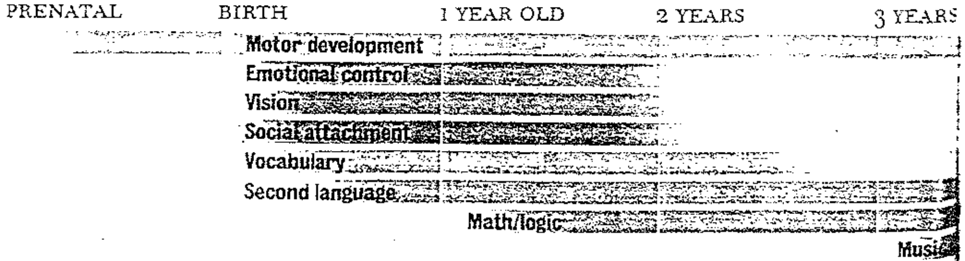
Force of habit rules the hallways and classrooms. Neither brain science nor education research has been able to free the majority of America's schools from their 19th-century roots. If more administrators were tuned into brain research, scientists argue, not only would schedules change, but subjects such as foreign language and geometry would be offered to much younger children. Music and gym would be daily requirements. Lectures, work sheets and rote memorization would be replaced by hands-on materials, drama and project work. And teachers would pay greater attention to children's emotional connections to subjects. "We do more education research than anyone else in the world," says Frank Vellutino, a professor of educational psychology at State University of New York at Albany, "and we ignore more as well."

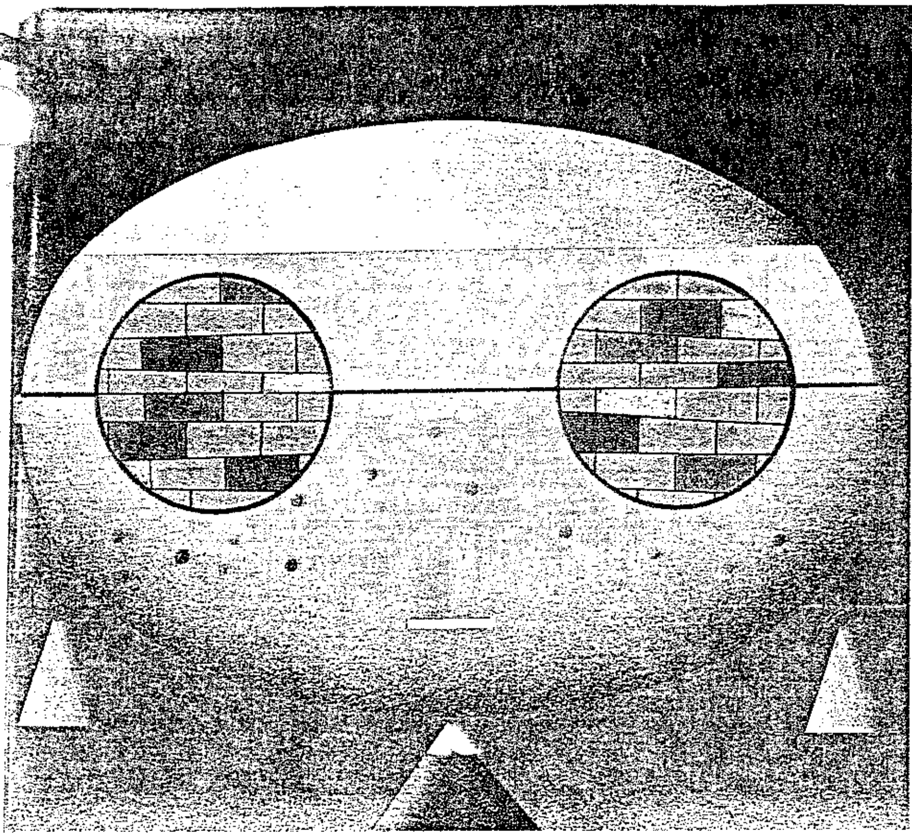
Plato once said that music "is a more potent instrument than any other for education." Now scientists know why. Music, they believe, trains the brain for higher forms of thinking. Researchers at the University of California, Irvine, studied the power of music by observing two groups of preschoolers. One group took piano lessons and sang daily in chorus. The other did not. After eight months the musical 3-year-olds were expert puzzlemasters, scoring 80 percent higher than their playmates did in spatial intelligence—the ability to visualize the world accurately.

This skill later translates into complex math and engineering skills. "Early music training can enhance a child's ability to reason," says Irvine physicist Gordon Shaw. Yet music education is often the first "frill" to be cut when school budgets shrink. Schools on average have only one music teacher for every 500 children, according to the National Commission on Music Education.

Then there's gym—another expendable hour by most school standards. Only 36 percent of schoolchildren today are required to participate in daily physical education. Yet researchers now know that exercise is good not only for the heart. It also juices up the brain, feeding it nutrients in the form of glucose and increasing nerve connections—all of which make it easier for kids of all ages to learn. Neuroscientist William Greenough confirmed this by watching rats at his University of Illinois at Urbana-Champaign lab. One group

The Windows of Opportunity





did nothing. A second exercised on an automatic treadmill. A third was set loose in a Barnum & Bailey obstacle course requiring the rats to perform acrobatic feats. These "supersmart" rats grew "an enormous amount of gray matter" compared with their sedentary partners, says Greenough.

Of course, children don't ordinarily run such gantlets; still, Greenough believes, the results are significant. Numerous studies, he says, show that children who exercise regularly do better in school.

The implication for schools goes beyond simple exercise. Children also need to be more physically active in the classroom, not sitting quietly in their seats memorizing subtraction tables. Knowledge is retained longer if children connect not only aurally but emotionally and physically to the material, says University of Oregon education professor Robert Sylwester in "A Celebration of Neurons."

Good teachers know that lecturing on the American Revolution is far less effective than acting out a battle. Angles and dimensions are better understood if children chuck their work sheets and build a complex model to scale. The smell of the glue enters memory through one sensory system, the touch of the wood blocks another, the sight of the finished model still another. The brain then creates a multidimensional mental model of the experience—one easier to retrieve. "Explaining a smell," says Sylwester, "is not as good as actually smelling it."

Scientists argue that children are capable of far more at younger ages than schools generally realize. People obviously continue learning their whole lives, but the optimum "windows of opportunity for learning" last until about the age of 10 or 12, says Harry Chugani of Wayne State University's Children's Hospital of Michigan. Chugani determined this by measuring the brain's consumption of its chief energy source, glucose. (The more glucose it uses, the more active the brain.) Children's brains, he observes, gobble up glucose at twice the adult rate from the age of 4 to puberty. So young brains are as primed as they'll ever be to process new information. Complex subjects such as trigonometry or foreign language shouldn't wait for puberty to be introduced. In fact, Chugani says, it's far easier for an elementary-school child to hear and process a second language—and even speak it without an accent. Yet most U.S. districts wait until junior high to introduce Spanish or French—after the "windows" are closed.

Reform could begin at the beginning. Many sleep researchers now believe that most teens' biological clocks are set later than those of their fellow humans. But high school starts at 7:30 a.m., usually to accommodate bus schedules. The result can be wasted class time for whole groups of kids. Making matters worse, many kids have trouble readjusting their natural sleep rhythm. Dr. Richard Allen of Johns Hopkins University found that teens went to sleep at the same time whether they had to be at school by 7:30 a.m. or 9:30 a.m. The later-to-rise teens not only get more sleep, he says; they also get better grades. The obvious solution would be to start school later when kids hit puberty. But at school, there's what's obvious, and then there's tradition.

Why is this body of research rarely used in most American classrooms? Not many administrators or school-board members know it exists, says Linda Darling-Hammond, professor of education at Columbia University's Teachers College. In most states, neither teachers nor administrators are required to know much about how children learn in order to be certified. What's worse, she says, decisions to cut music or gym are often made by noneducators, whose concerns are more often monetary than educational. "Our school system was invented in the late 1800s, and little has changed," she says. "Can you imagine if the medical profession ran this way?"

With Pat Wingert *and* Mary Hager *in Washington*

Circuits in different regions of the brain mature at different times. As a result, different circuits are most sensitive to life's experiences at different ages. Give your children the stimulation they need when they need it, and anything's possible. Stumble, and all bets are off.

ARS | 4 YEARS | 5 YEARS | 6 YEARS | 7 YEARS | 8 YEARS | 9 YEARS

sic

Movement: Fetal movements begin at 7 weeks and peak between the 15th and 17th weeks. That is when regions of the brain controlling movement start to wire up. The critical period lasts a while: it takes up to two years for cells in the cerebellum, which controls posture and movement, to form functional circuits. "A lot of organization takes place using information gleaned from when the child moves about in the world," says William Greenough of the University of Illinois. "If you restrict activity you inhibit the formation of synaptic connections in the cerebellum." The child's initially spastic movements send a signal to the brain's motor cortex; the more the arm, for instance, moves, the stronger the circuit, and the better the brain will become at moving the arm intentionally and fluidly. The window lasts only a few years: a child immobilized in a body cast until the age of 4 will learn to walk eventually, but never smoothly.

THERE ARE MANY more circuits to discover, and many more environmental influences to pin down. Still, neuro labs are filled with an unmistakable air of optimism these days. It stems from a growing understanding of how, at the level of nerve cells and molecules, the brain's circuits form. In the beginning, the brain-to-be consists of only a few advance scouts breaking trail: within a week of conception they march out of the embryo's "neural tube," a cylinder of cells extending from head to tail. Multiplying as they go (the brain adds an astonishing 250,000 neurons per minute during gestation), the neurons clump into the brain stem which commands heartbeat and breathing, build the little cerebellum at the back of the head which controls posture and movement, and form the grooved and rumpled cortex wherein thought and perception originate. The neural cells are so small, and the distance so great, that a neuron striking out for what will be the prefrontal cortex migrates a distance equivalent to a human's walking from New York to California, says developmental neurobiologist Mary Beth Hatten of Rockefeller University.

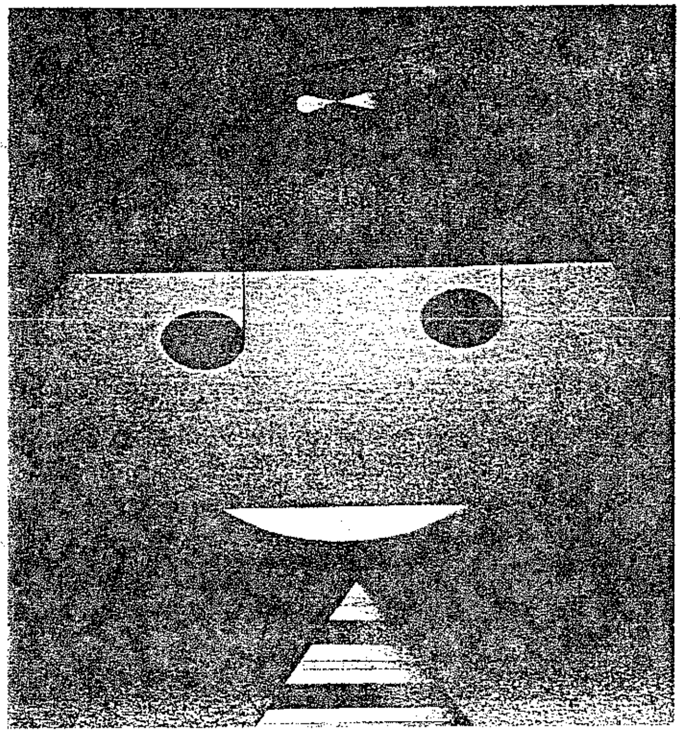
Only when they reach their destinations do these cells become true neurons. They grow a fiber called an axon that carries electrical signals. The axon might reach only to a neuron next door, or it might wend its way clear across to the other side of the brain. It is the axonal connections that form the brain's circuits. Genes determine the main highways along which axons travel to make their connection. But to reach particular target cells, axons follow chemical cues strewn along their path. Some of these chemicals attract: this way to the motor cortex! Some repel: no, *that* way to the olfactory cortex. By the fifth month of gestation most axons have reached their general destination. But like the prettiest girl in the bar, target cells attract way more suitors—axons—than they can accommodate.

How does the wiring get sorted out? The baby neurons fire electrical pulses once a minute, in a fit of what Berkeley's Shatz calls auto-dialing. If cells fire together, the target cells "ring" together. The target cells then release a flood of chemicals, called trophic factors, that strengthen the incipient connections. Active neurons respond better to trophic factors than inactive ones, Barbara Barres of Stanford University reported in October. So neurons that are quiet when others throb lose their grip on the target cell. "Cells that fire together wire together," says Shatz.

The same basic process continues after birth. Now, it is not an auto-dialer that sends signals, but stimuli from the senses. In experiments with rats, Illinois's Greenough found that animals raised with playmates and toys and other stimuli grow 25 percent more synapses than rats deprived of such stimuli.

Rats are not children, but all evidence suggests that the same rules of brain development hold. For decades Head Start has fallen short of the high hopes invested in it: the children's IQ gains fade after about three years. Craig Ramey of the University of Alabama suspected the culprit was timing: Head Start enrolls 2-, 3- and 4-year-olds. So in 1972 he launched the Abecedarian Project. Children from 120 poor families were assigned to one of four groups: intensive early education in a day-care center from about 4 months to age 8, from 4 months to 5 years, from 5 to 8 years, or none at all. What does it mean to "educate" a 4-month-old? Nothing fancy: blocks, beads, talking to him, playing games such as peek-a-boo. As outlined in the book "Learningames,"* each of the 200-odd activities was designed to enhance cognitive, language, social or motor development. In a recent paper, Ramey and Frances Campbell of the University of North Carolina report that children enrolled in Abecedarian as preschoolers still scored higher in math and reading at the age of 15 than untreated children. The children still retained an average IQ edge of 4.6 points. The earlier the children were enrolled, the more enduring the gain. And intervention after age 5 conferred no IQ or academic benefit.

*Joseph Sparling and Isabelle Lewis (226 pages. Walker. $8.95).



The Musical Brain

SKILL: Music

LEARNING WINDOW: 3 to 10 years

WHAT WE KNOW: String players have a larger area of their sensory cortex dedicated to the fingering digits on their left hand. Few concert-level performers begin playing later than the age of 10. It is much harder to learn an instrument as an adult.

WHAT WE CAN DO ABOUT IT: Sing songs with children. Play structured, melodic music. If a child shows any musical aptitude or interest, get an instrument into her hand early.

All of which raises a troubling question. If the windows of the mind close, for the most part, before we're out of elementary school, is all hope lost for children whose parents did not have them count beads to stimulate their math circuits, or babble to them to build their language loops? At one level, no: the brain retains the ability to learn throughout life, as witness anyone who was befuddled by Greek in college only to master it during retirement. But on a deeper level the news is sobering. Children whose neural circuits are not stimulated before kindergarten are never going to be what they could have been. "You want to say that it is never too late," says Joseph Sparling, who designed the Abecedarian curriculum. "But there seems to be something very special about the early years."

And yet . . . there is new evidence that certain kinds of intervention can reach even the older brain and, like a microscopic screwdriver, rewire broken circuits. In January, scientists led by Paula Tallal of Rutgers University and Michael Merzenich of UC San Francisco described a study of children who have "language-based learning disabilities"—reading problems. LLD affects 7 million children in the United States. Tallal has long argued that LLD arises from a child's inability to distinguish short, staccato sounds—such as "d" and "b." Normally, it takes neurons in the auditory cortex something like .015 second to respond to a signal from the ear, calm down and get ready to respond to the next sound; in LLD children, it takes five to 10 times as long. (Merzenich speculates that the defect might be the result of chronic middle-ear infections in infancy: the brain never "hears" sounds clearly and so fails to draw a sharp auditory map.) Short sounds such as "b" and "d" go by too fast—.04 second—to process. Unable to associate sounds with letters, the children develop reading problems.

The scientists drilled the 5- to 10-year-olds three hours a day with computer-produced sound that draws out short consonants, like an LP played too slow. The result: LLD children who were one to three years behind in language ability improved by a full two years after only four weeks. The improvement has lasted. The training, Merzenich suspect, redrew the wiring diagram in the children's auditory cortex to process fast sounds. Their reading problems vanished like the sounds of the letters that, before, they never heard.

Such neural rehab may be the ultimate payoff of the discovery that the experiences of life are etched in the bumps and squiggles of the brain. For now, it is enough to know that we are born with a world of potential—potential that will be realized only if it is tapped. And that is challenge enough.

With MARY HAGER

Private dancer: *Money changes hands at the Cheetah*

OLYMPICS

Not Only Divers Work Topless

Fighting over a 'modeling studio'

BY VERN E. SMITH

IN ATLANTA THEY ARE CALLED "LINGERIE modeling studios." In practice, they offer private sessions with young women who, among other things, strut about in their underwear. Most locals pretty much ignore the whole business except when a visitor asks where the action is. This summer, though, the whole world is coming to Atlanta for the Summer Olympics, and this bit of rococo Southern hospitality is embarrassing city officials.

As it so often is when morality and real estate intersect, the problem is one of location. To give Games-goers a place to go in the midday sun, both the Olympic organizers and Coca-Cola have invested millions of dollars to create hospitality parks in the center of town. While all of that was being planned, one enterprising businessman leased space directly across the street from one of these parks with a plan of his own: to open the XCLUSIVE! Lingerie Studio. Ted Parabak has painted the currently empty building a fetching purple and green and put up a sign and intends to wait for the overflow from the other Games in town.

At first, a city agency dutifully approved his plans. But a highly perturbed Mayor Bill Campbell sent the application back to the city's License Review Board. He argues that the Lingerie Studio violates city zoning, which requires a 1,000-foot buffer between such establishments and public spaces where children may be present. XCLUSIVE is only 400 feet from Centennial Park, says Campbell, who's also concerned that a lingerie joint is not compatible with the area's post-Olympics development.

A jump start: Parabak's lawyer Alan Begner threatens to sue if the license is rejected. Parabak's only public comment suggests he is banking on the Games to help jump-start his studio, especially with European visitors. "They are *very* familiar with adult entertainment, if you know what I mean," Parabak told The Atlanta Constitution. "I hope we can stay in business because what they have there is tame in comparison."

That may just be local pride talking. Atlanta ranks third (behind New York and Chicago) as a national convention center, and first in its region in strip joints. Hosting more than 2,000 conventions and major meetings a year, Atlanta's hospitality industry grosses more than $3 billion annually. Officially, the most popular local tourist attraction is Underground Atlanta, a shopping-dining-entertainment complex that draws 10 million visitors a year. But unofficially, the nearly 50 nude clubs and roughly a dozen lingerie studios have proven a hot draw for visitors. All told, the take from Atlanta's adult-entertainment scene could top $200 million annually, according to Donald Ratajczak, an economics professor at Georgia State University.

Georgia has tried to close this industry in the past. Before Atlanta hosted the 1988 Democratic convention, the legislature banned nude dancing in places where alcohol was served. To serve that year's conventioneers, bar owners put some clothes on their dancers. When the Georgia Supreme Court struck down the law, the pasties came off and nude clubs sprang up in the suburbs, too. This summer they may be giving out medals.