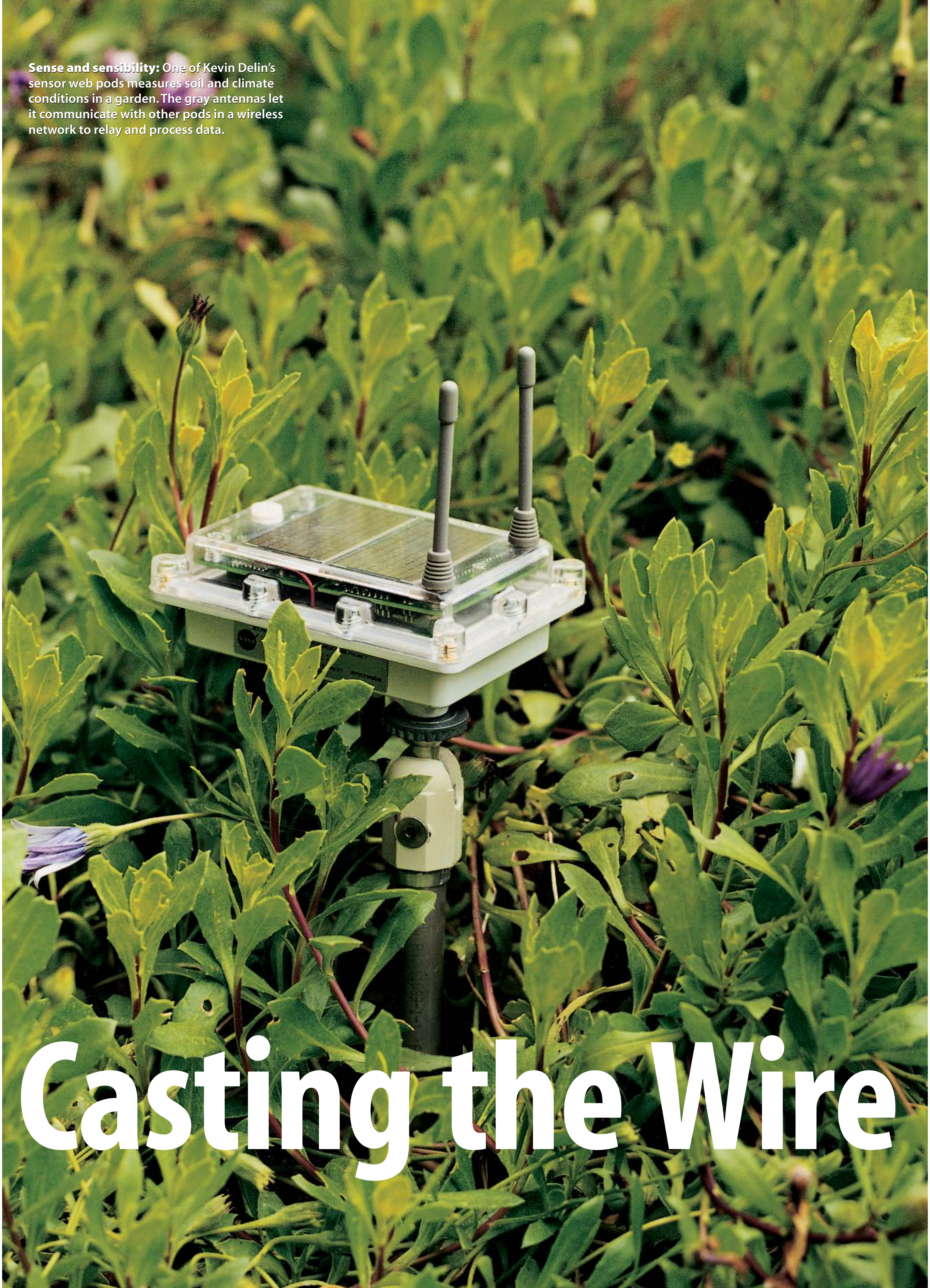


Sense and sensibility: One of Kevin Delin's sensor web pods measures soil and climate conditions in a garden. The gray antennas let it communicate with other pods in a wireless network to relay and process data.

Casting the Wire

I DIDN’T KNOW THIS BEFORE, BUT PLANTS HAVE SEX,” SAYS KEVIN DELIN. He’s gesturing toward two huge cycads, palmlike fugitives from the Dinosaur Age growing in a corner of the Huntington Botanical Gardens, a sanctuary for 15,000 rare plant species in San Marino, CA. Delin’s ignorance of botany is excusable. He’s an engineer from NASA’s nearby Jet Propulsion Laboratory, and what truly interest him are not the male and female cycads but the pair of “sensor web pods” lodged in the ground under the plants. Each pod is the size of a handheld computer and contains a processor, battery, solar cell, radio, memory, and sensors to monitor heat, humidity, and soil moisture. The pods are the surrogate eyes, ears, and even brains of the garden’s curators, keeping track of how much sunlight and rain the plants are getting—critical factors for cycads, which need specific conditions to reproduce.

Sensors are nothing new. A car, for instance, uses dozens of them to monitor factors such as engine conditions. But the sensors in today’s automobiles, factories, and office buildings are, for the most part, dumb. They lack the intelligence to analyze or act on their findings; instead, they send measurements back to a central processor. Most current sensors are also stuck in place, with any move requiring expensive rewiring. Delin’s pods are different. They talk wirelessly with each other and with 18 other pods in the garden, forming their own intelligent network. Every few minutes, the pods update each other about their latest readings, together process the information into an overall picture of temperature and soil conditions, and send this analysis to the curators. It’s as if an autonomous, highly aware computer were spread across 40 hectares of landscape.

“It’s all about synthesizing global knowledge from raw data on the fly,” says Delin. His pods foretoken a future where smart sensors suck in vast amounts of vital data—say, mechanical stresses on the beams of a bridge, or the rumble of an enemy convoy on a moonless desert night—that currently go unrecorded. Wireless and battery-powered, such sensors will be accessed remotely and put where it would be impractical to string data and power lines. Small and cheap, they will be liberally distributed and closely spaced, yielding fine-grained pictures of phenomena such as climate that are currently charted only on a large scale. And because they will act cooperatively—organizing themselves and sharing computations across the mesh—they will provide people with usable chunks of predigested information rather than a confusing wash of numbers.

A WIRELESS MESH OF SENSING AND COMPUTING DEVICES WILL TRANSFORM THE WAY WE MANAGE OUR HOMES, FACTORIES, AND ENVIRONMENT.

Indeed, wireless sensor networks are one of the first real-world examples of “pervasive” computing, the notion that small, smart, and cheap sensing and computing devices will eventually permeate the environment. That notion has been percolating in information technology circles for more than a decade. But now, after several years of research investments by the U.S. Defense Advanced Research Projects Agency, the National Science Foundation, and a handful of high-tech giants like Intel, the hardware and software fundamental to pervasive computing are emerging.

less Sensor Net

BY GREGORY T. HUANG

PHOTOGRAPHS BY DAVE LAURIDSEN

Though the technology is still in its early days, the range of potential applications is mind-boggling. Scientists at Intel and the University of California, Berkeley, have developed a wireless, pager-sized "chassis" that can be customized with many kinds of sensors. The researchers are using the devices to track micro-climates and pests in vineyards, monitor the nesting habits of rare sea birds, and control heating and ventilation systems. And 600 kilometers down the road at the University of California, Los Angeles, other researchers are deploying wireless sensors to gain detailed measurements of the effects of seismic waves on buildings. Still others are working on ways to let businesses monitor and control their work spaces, from local offices to assembly lines half a continent away. "The applications are *everywhere*," says David Culler, a leading networked-sensing researcher at UC Berkeley.

In the minds of many, it's a technology that could prove as important as the Internet: for just as the Internet allows computers to tap digital information no matter where it's stored, sensor networks will expand people's ability to remotely interact with the physical world. Culler calls the devices "a new class of computer systems," distinguished from the hardware of the past by their ubiquity and their collective analytical skill. Within this decade, he predicts, distributed sensing and computing will creep into every home, building, office, factory, car, street, and farm.

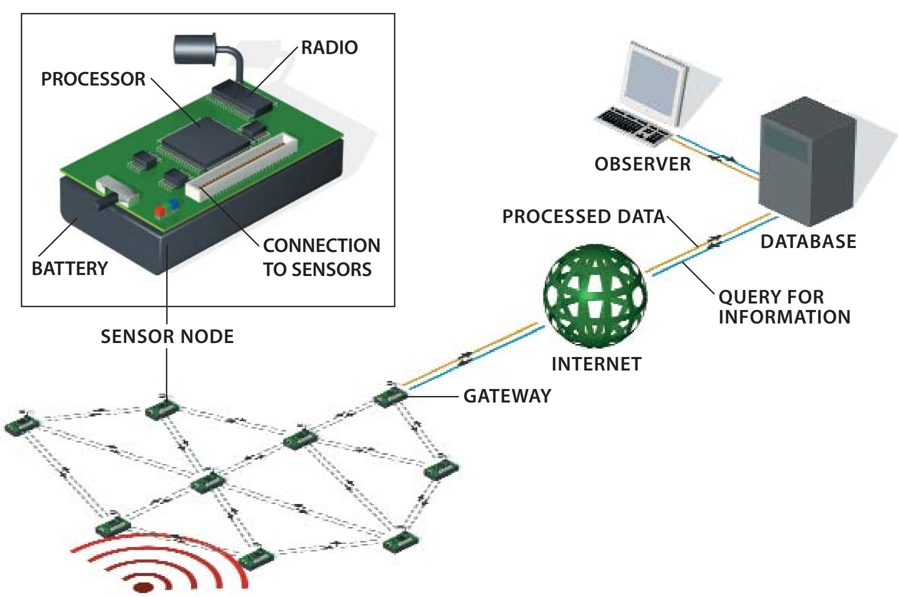
Not surprisingly, there are plenty of challenges before that happens. In many ways, wireless sensor webs are as far along as the Internet was in the 1970s, when the network linked fewer than 200 universities and military labs, and researchers were still experimenting with communications protocols and address schemes. Today, most wireless sensor networks connect fewer than 100 points, or "nodes"; any more and the lines of communication become so tangled that they break down. The cost of the average node is close to $100, while battery life is measured in, at best, months. And no one is exactly sure what application will transform the technology into a commercial bonanza. "Everyone and their aunt and uncle is interested," says Deborah Estrin, director of UCLA's Center for Embedded Networked Sensing. "But it's a struggle to find the business model."

Researchers say none of these problems is likely to be prohibitive. Some wireless sensors are already on the market, and products with intriguing new capabilities could be available within a few years. Sensoria in San Diego, for one, is developing sensors that could turn cars into traveling nodes in urban wireless networks, allowing groups of vehicles to automatically assemble real-time pictures of local traffic or to share communications duties when accessing information about local destinations. William Kaiser, a UCLA electrical engineer and founder of Sensoria, maintains, "The Internet changed how we do business with computers. This will change the way we live our everyday lives."

"THE INTERNET CHANGED HOW WE DO BUSINESS WITH COMPUTERS. THIS WILL CHANGE THE WAY WE LIVE OUR EVERYDAY LIVES."

Anatomy of a Wireless Sensor Net

An environmental disturbance (red) is sensed by nodes in the network. They send radio signals to one another (dashed lines) and process the data—predicting, say, the spread of toxic chemicals or seismic waves. A human observer can remotely access the crucial information.



JOHN MACNEILL

UNWIRING INDUSTRY

Back at the Huntington gardens, Delin enters a conference room bearing an aluminum briefcase, the kind government agents on TV use to carry top-secret gadgets. He takes out four of his latest sensor pods and pries the cover off of one; underneath are circuit boards holding the pod's guts, including the microprocessor and the radio transceiver that lets it communicate with its companions. He spreads the pods around the room, and within seconds they locate one another and self-organize into a wireless network that monitors temperature and humidity, among other things. A nearby pod—though any of them would do—forwards information from the network to Delin's laptop for display. To show how the network reacts to its environment, Delin disconnects one of the devices. The laptop screen shows the remaining pods compensating by routing data around the missing pod. He attaches an electric fan to one pod, then holds another pod in his hand; the network detects Delin's body heat and switches on the fan.

The pods' ability to communicate by radio, Delin explains, means that they can be scattered in areas that phone and power lines don't reach and moved around at will. But to get data flowing, nodes must find their neighbors automatically and set up radio connections. Those connections can change rapidly, says Delin, so sharing data over the network is a juggling act. Software running

Factory net: A solar-powered Xsilogy node (yellow) receives data from a water-pump sensor (inset) and beams it to the network.

COURTESY OF XSILOGY

on all of the pods coordinates which of them talk to one another and when. The sensor nodes "listen" for one another and set up times to share data, while a network clock keeps the nodes in sync. The network resembles a mesh rather than the hub-and-spoke arrangement used for cell phones; instead of linking each sensor directly to a central communication point, the nodes send data only to neighbors within radio range, saving power.

It sounds complicated, and it is. But decentralized wireless networks like Delin's are already cost effective for heavy industry: Ember in Boston, MA, has sold similar technology to customers frustrated with the conventional wired sensors in their manufacturing or heating and ventilation equipment. One customer used to line the pipes of its treatment plant—where oil and gas are separated from wastewater—with expensive wired temperature sensors, attached to heaters that keep the fluid inside from becoming too thick. If a sensor malfunctioned, a tank could burst, forcing the plant to shut down at a cost of $100,000 per hour, says Robert Poor, Ember's cofounder and chief technology officer. With a wireless network, more sensors can be installed at an affordable price, offering redundancy and yielding more reliable information. "Silicon is cheap. Wiring is not," Poor says.

Several remaining problems, however, obstruct broad commercial application of the technology. The first is its high power consumption. The periodic talk back and forth between the nodes, in particular, is a drain on batteries. "Every bit transmitted brings a sensor node one moment closer to death," says Greg Pottie, a Sensoria cofounder.

A related issue is that sensor nodes' radios have a limited range, usually in the tens of meters. So networking a bigger space—say, a large factory—takes a lot of nodes. Numerous nodes sending lots of data create opportunities for localized failures that could leave parts of the network isolated, says Rick Kriss, CEO of San Diego-based Xsilogy. "There's no such thing as a reliable network, unless you do very aggressive network management," Kriss says. So Xsilogy's nodes periodically broadcast their status, letting the network know if their batteries are running low or their reception is fading. Then the network can compensate by routing around the failure points and alerting the user to impending problems.

High-wireless act: Networked sensors on the ceiling of Deborah Estrin's UCLA lab monitor heat, light, and motion. The researchers are testing ways to process and route data efficiently.

But there's another problem that is harder to work around, and that's price. In a process that is the very opposite of mass production, most sensor-net makers still cobble together off-the-shelf parts by hand, raising the cost of each node into the $80 to $100 range. That price needs to drop below $20 in order for sensor nets to take off commercially, says David Tennenhouse, director of research at Intel.

Standardization could help. "Having open standards and many disinterested groups testing competing approaches will absolutely make or break whether this becomes widely used," says UC Berkeley's Culler. But with so many companies and university labs developing their own prototypes, design standards for wireless sensors and networking protocols are only beginning to emerge. One potentially dominant design is called a "mote"; its operating system, TinyOS, was developed by Culler's group at Berkeley and is undergoing further refinements at Intel and Crossbow Technology in San Jose, CA. The Berkeley motes, which have been tested by hundreds of research groups around the world, are smaller and use less power than most commercial wireless sensors. The trade-off is that they can't process as much data. But many researchers say their adaptability—it's easy to snap on sensors for light, sound, temperature, or movement, say—makes them the networked-sensor world's equivalent of a Windows PC.

A SENSOR NETWORK SHOULD SEND ONLY ITS ANALYSES, NOT THE RAW BITS THEMSELVES. USERS "WANT ANSWERS, NOT NUMBERS."

In fact, the eventual choice of a wireless-sensor platform could be just as consequential as the emergence of Windows as the dominant consumer operating system—or even, in the eyes of one expert, as the standardization of electricity. "It is sort of like the historic battle between AC and DC," says Larry Smarr, director of the California Institute for Telecommunications and Information Technology in San Diego. "Until there was a ubiquitous winner, the electrical-appliance industry couldn't take off."

DIVIDE AND CONQUER

As if ready to take off themselves, 50-odd butterfly-sized motes cling to the ceiling and walls of Deborah Estrin's lab at UCLA, monitoring temperature, light, and motion. Others lie dismantled on desktops and benches. A few of the motes even have wheels; they roll across the floor under their own propulsion, practicing for a day when they'll move around to find the best radio reception or deliver a battery recharge to a failing neighbor. "Here's a picture of the connectivity," says Estrin, holding up a sheet of paper with an incomprehensible tangle of lines on it. It looks like a plate of spaghetti: the number of communication pathways explodes as more nodes are added, making the network more and more crash-prone.

The solution being tested in Estrin's lab: divide and conquer. Think of it as organizing a big dinner party, she says. Meaningful conversations can't occur unless people take turns speaking and listening. And high-level communication is most efficient if people organize themselves into clusters and elect an individual to speak for each cluster. Therefore the nodes cluster themselves and adjust on the fly, changing clusters opportunistically to optimize both power consumption and the flow of information through the network.

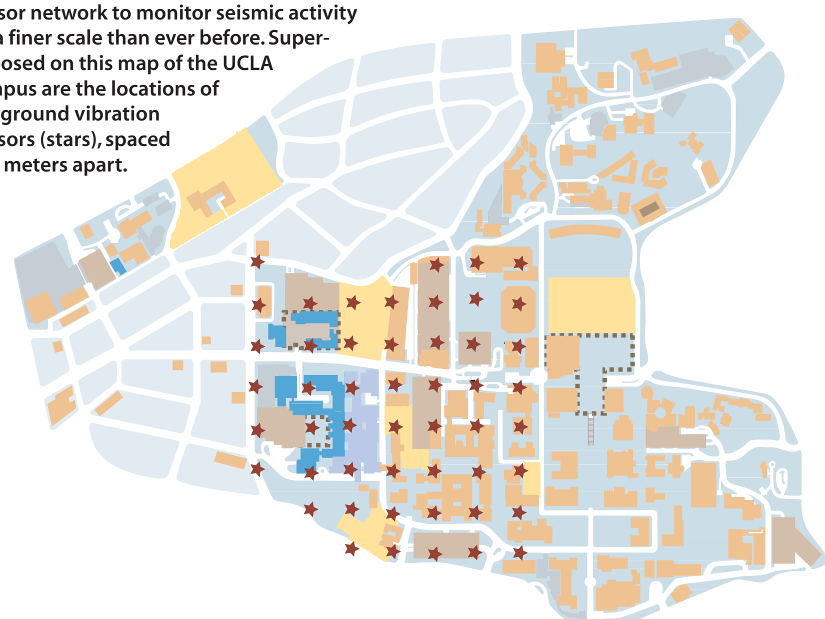
The next challenge is simply how to channel the flood of data. The idea is to put processing into each node, allowing it to condense raw data into patterns and pass along fewer bits than it received. The motes above Estrin's head, for example, could follow her movements and alert their neighbors, which figure out the direction she's walking and transmit just that information—not the entire record of her movements—to a database on a mother node. This node can recommend that lights be turned off, for example, if it decides that Estrin has left the room and no other people are present. Processing data a little at a time throughout the network, says Estrin, is a first step toward programming the system to help make intelligent decisions. It also saves precious battery power.

To be truly useful, a sensor network should send users only its analyses of interesting events, not the raw bits themselves. "People want answers, not numbers," points out Steven Glaser, a professor of civil and environmental engineering at UC Berkeley whose group uses sensor nets to study seismic activity.

Among the answers that engineers and seismologists like Glaser want: how do earthquakes affect individual components of buildings, and how do structures respond to localized variations in an earthquake's strength? A UCLA team led by Paul Davis, a geophysicist and principal investigator at Estrin's center,

Seismic Sensing

Researchers at UCLA are deploying a 50-node sensor network to monitor seismic activity on a finer scale than ever before. Superimposed on this map of the UCLA campus are the locations of the ground vibration sensors (stars), spaced 100 meters apart.



COURTESY OF PAUL DAVIS AND ALLEN HUSKER (MAP) is deploying a 50-node array of seismic sensors across the campus in an attempt to learn part of the answer. The first step is just to accumulate the data, recorded from the ground at 100-meter intervals—a much higher resolution than that provided by current seismic sensors, which are spaced kilometers apart, says Davis. The researchers will then compare how the ground shakes to vibrations measured at the same time inside a campus building wired by the U.S. Geological Survey after the Northridge, CA, quake of 1994.

The goal is to develop a model of how fine-scale seismic activity affects different structures. Such a model—programmed into portable sensor nets that could be deployed temporarily in city neighborhoods—could help urban planners learn where geological conditions tend to magnify quakes and how to make buildings in those areas safer. In the future, sensors placed near fault lines could even detect approaching seismic waves and trigger alarms, giving building occupants precious seconds to get to safer areas. But, Davis says, "That's blue-sky stuff."

TRANSLATING TODAY'S SENSOR-NET RESEARCH INTO PRODUCTS MAY SIGNIFY A MERGER BETWEEN THE VIRTUAL AND PHYSICAL WORLDS.

GOOGLE FOR THE PHYSICAL WORLD

Smart, autonomous, and self-aware: that's the ultimate vision for sensor nets. In many ways, it *is* blue-sky. But two industry projects provide glimpses of a networked future.

There is a danger that accessing the data collected by sensor networks will be like "drinking from a fire hose, only worse," says Feng Zhao, manager of the Embedded Collaborative Computing research area at the Palo Alto Research Center in California. In other words, being inundated with too much data can be just as paralyzing as not having enough. It's a dilemma that anyone using the Web is well aware of. And, says Zhao, the solution for sensor networks may be similar. In an effort to construct user-friendly interfaces for sensor networks, Zhao's group is experimenting with a new breed of search engine that he describes as "like Google for the physical world."

Imagine, Zhao explains, logging onto the Internet and typing in, "Does my lawn need more water?" The network would translate the question into a standardized database query, examine figures from moisture sensors around your home, and send back a prompt yes or no. Similar systems for supply chain management and security could be available in five to seven years, says Zhao. At warehouses, managers could quiz shelf-mounted sensors about inventory trends, while guards in secure facilities could program smart networks of motion sensors to sound alarms when they notice suspicious patterns of movement.

Eventually, sensor nets may even seem alive. At a U.S. Army base in Fort Leonard Wood, MO, this April, Sensoria engineers demonstrated a disturbingly self-aware system that physically rearranges itself in response to changing conditions. As 80 spectators watched, an M1-A1 Abrams battle tank rumbled across a field with a plow attached to its front, blazing a trail through a thicket of unarmed, 12-centimeter-diameter mines. After the tank crushed a half-dozen or so of the mines and proceeded on its way, the remaining mines redistributed themselves to fill the gap behind the tank—hopping through the air with firecracker pops emanating from tiny rocket boosters.

The mines accomplished this feat by emitting and listening for acoustic pulses that helped them locate their neighbors to within a few centimeters, says Kaiser. A disturbance in the network prompts the mines to figure out which neighbors have been moved or destroyed and calculate how to redistribute themselves. On a real battlefield, such smart mines could defeat enemy mine-clearing efforts, or even move out of the way for friendly forces and then reestablish defenses behind them.

Despite such dramatic demonstrations of the power of wireless sensor nets, it's hard to predict whether defense, manufacturing, or some as-yet-unknown field will play host to their killer app. "It's like PCs in the early 1980s. People thought they would be used mainly to balance checkbooks," says Delin. As for the near-term commercial market, it will be a "delectably messy environment for a while," with plenty of opportunity for newcomers, predicts Ember's Poor. That's because the potential applications are all around us—anywhere useful information can be extracted from our environment. When today's research is translated into inexpensive, crashproof products, it may signify nothing short of a merger between the virtual world and the physical world. "It's going to happen," says Zhao. "The question is, how soon?"

Sensing the Potential

COMPANY	TECHNOLOGY	APPLICATIONS
Crossbow Technology (San Jose, CA)	Modular motes with interchangeable sensors	Environmental monitoring, security
Dust (Berkeley, CA)	Four-square-millimeter motes	Inventory tracking, surveillance
Ember (Boston, MA)	Self-organizing nodes and software	Building and factory automation, defense
Intel (Santa Clara, CA)	Modular motes with interchangeable sensors	Monitoring of farm, wildlife, and manufacturing sites
Millennial Net (Cambridge, MA)	Dime-size, low-power nodes and software	Building automation, meter reading, supply chain management
Sensicast Systems (Needham, MA)	Mesh-networking software for sensors	Museum security, landscaping, horticulture
Sensoria (San Diego, CA)	High-performance nodes and software	Defense networks, automotive and health-care systems
Xsilogy (San Diego, CA)	Radios, sensors, and networking software	Industrial and equipment monitoring, heating and ventilation