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Ubiquitous computing

Mark Weiser, Xerox Corporation

If technological advances were simply a continuous, linear outgrowth of past technology, we might expect future computing environments merely to comprise more laptops possessing more power, more memory, and better color displays. But the world of information and technology doesn't always evolve linearly. Radical new uses of portable information technology are on the horizon.

To better envision future technology, we need to examine the work environment, for two distinct crosscurrents will shape future personal information subsystems. Counterposed against the technological leaps that are now being glimpsed is the very human desire not to be held hostage by that technology.

Current thought about the work environment places significant emphasis on unobtrusive technology. The best user interface is the self-effacing one, the one that you don't even notice. At the same time, the amount of information impinging upon our lives is exploding, often via high-tech media (cable home shopping, interactive television, computer bulletin boards, and so on). Thus, on one level we have increasing unobtrusiveness, and on another even more intrusiveness.

The paradoxical intersection of these two conflicting trends leads me to believe that the next phase of computing technology will develop nonlinearly. Without being too fanciful, we might even anticipate a renaissance similar to that stemming from Gutenberg's invention of movable type. Before Gutenberg, information was expensive, tightly controlled, precious. Today, it effortlessly (and often unobtrusively) surrounds us. Look around now: How many objects and surfaces do you see with words on them? Computers in the workplace can be as ubiquitous as today's printed matter. In the long run, the personal computer and the workstation will become practically obsolete because computing access will be everywhere: in the walls, on your wrist, and in "scrap computers" (like scrap paper) lying about to be used as needed. Hence, *ubiquitous computing.*

What it is and what it will do for you. Ubiquitous computing has as its goal the nonintrusive availability of computers throughout the physical environment, virtually, if not effectively, invisible to the user.

Unlike virtual reality, ubiquitous computing will integrate information displays into the everyday physical world. Its proponents value the nuances of the real world and aim only to augment them. And unlike current personal digital assistants, ubiquitious computing will be a world of fully connected devices, with cheap wireless networks; it will not require that you carry around a PDA, since information will be accessible everywhere.

Nascent research in ubiquitous computing has already had a worldwide impact on all areas of computer science, from hardware components to network protocols, interaction substrates, applications, privacy, and computational methods.

Unlike the intimate agent computer that responds to your voice and is a personal assistant, ubiquitous computing takes place primarily in the background. Whereas the intimate computer does your bidding, the ubiquitous computer leaves you feeling as though you did it yourself. Its extensive use of video and audio, including voice communication, will transform electronic interfaces into interpersonal ones. The hundreds of little displays in the future office will replace the thousands of words visible in today's office (on book spines, wall postings, phone messages, working papers, and Post-its) and will be seamlessly integrated into the work environment, gently enhancing the occupants' everyday activities.

Current research. Work on ubiquitous computing is still at an early phase and is for the most part focused on the mobile infrastructure for wireless networking. Still, this nascent research has already had a worldwide impact on all areas of computer science, from hardware components to network protocols, interaction substrates (for example, software for screens and pens), applications, privacy, and computational methods.

Because ubiquitous computing will involve hundreds of wireless computers in every office, its need for wireless bandwidth will be substantial. For instance, I work in a building with 300 other people. If each of us were to have 100 wireless devices (plausible, since a typical office or home has many more information sources than this now) in our offices, each demanding 256 Kbits per second, we would require 7.5 gigabits of aggregate bandwidth. This is difficult to achieve with current wireless technologies. The crucial issue is not the usual bits per second, but bits per second per cubic meter, where the final divisor is the volume of space over which a given data source can be heard. One way to achieve gigabits of aggregate bandwidth in a building is to use a radio or infrared cellular system, with cells the size of an office, so that the same frequency band is reused hundreds of times in the same building.

A second challenge of the mobile infrastructure is mobility itself. Networking developed over the past 20 years with the assumption that a machine's name and its network address were unvarying. However, once a computer can move from network to network, this assumption no longer holds. Existing protocols such as TCP/IP and OSI need to be redesigned to handle machine mobility, and a number of committees and researchers are attempting to augment them or to design new protocols that can handle mobility. For example, the Mobile-IP Subcommittee of the Internet Engineering Task Force is considering a number of proposals by which a mobile device would have data packets rerouted from its home address to its current location.

A third challenge of the mobile infrastructure is window systems. Most window systems, such as those for the Macintosh and for DOS, cannot open remote windows over a network. Even window systems designed for networking, such as X Windows, have built-in assumptions about the mobility of people. The X Window System protocol, for instance, makes it very difficult to migrate the window of a running application from one screen to another, although this is just what a person traveling from his or her office to a meeting might want to do.

The growing number of researchers working on ubiquitous computing will surmount the daunting technical challenges. This leaves only the psychological, social, and business challenges. The most profound revolutions are not the ones trumpeted by pundits, but those that sneak in when we are not looking. Time will tell if ubiquitous computing, or something else, will be the next to quietly transform our lives.

Further reading

"Computer-Augmented Environments: Back to the Real World," *Comm. ACM*, Vol. 36, No. 7, July 1993.

Proc. Usenix Mobile and Location-Independent Computing Symp., Usenix Assoc., Berkeley, Calif., Aug. 1993.

B. McKibben, *The Age of Missing Information*, Penguin Books, New York, 1992.

M. Weiser, "The Computer for the Twenty-First Century," *Scientific American*, Vol. 265, No. 3, Sept. 1991, pp. 94-104.

Readers can learn more about ubiquitous computing through the Internet Engineering Task Force on Mobility (Steve Deering, chair). For more information, send e-mail to deering@xerox.com, or write Steve Deering at Xerox PARC.

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UPDATE

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Boundary element software speeds structure analysis

Century-old mathematical formulations not previously thought to have commercial utility have led to the development of an analysis method now being used in complex engineering problems that may involve stress analysis, heat transfer, fluid analysis, or the yielding and cracking of solids.

"With the boundary element method, you just model the outside boundary," said Ken Liao, senior engineer at the John Deere Product Engineering Center. "It automatically figures out the inside on its own."

"For the last 25 years, people have been saying it will never work," said Prasanta K. Banerjee, professor of civil engineering at the State University of New York (SUNY) at Buffalo. "Now, suddenly, it's looking very useful and very accurate."

The boundary element method functions on the premise that any homogeneous region of a system can be analyzed by being subdivided into sections consisting only of surfaces, not so-called whole-body or three-dimensional elements. By calculating the surfaces, Banerjee explained, predictions can be made about a system's internal behavior. So instead of making time-consuming volume calculations, the method solves 3D volume problems as 2D surface problems. Although the boundary element method involves extremely complicated mathematics, it is easily accommodated by desktop workstations.

In 1990, NASA, which partially funded Banerjee's efforts, publicly distributed his research software through Cosmic, the technology transfer arm of the Department of Commerce. While other boundary element software packages exist, the codes on which Banerjee's software is based are still the only ones available to the public.

Banerjee and his colleagues at the university are now applying the boundary element method to computational fluid dynamics and to composites.

To provide support services related to the research software, Banerjee created a boundary element software package that he distributes through the Boundary Element Software Technology Corp.

Biosphere project reaches milestone

A long-term scientific project in which researchers have been living inside the world's largest closed ecological life-support system has passed a significant milestone. The Biosphere II crew completed its two-year mission September 26, successfully sustaining themselves and approximately 3,500 species of plants and animals without using toxic pesticides or chemical fertilizers. The experiment is the first phase of a 100-year study of the interdependent ecology of Earth.

Biosphere II, built between 1987 and 1990 near Oracle, Arizona, makes extensive use of computer systems for administrative support, communication, and monitoring of ambient conditions (*Computer*, May 1989, p. 11). Except for personal and scientific journals, and the Biospherians' library, the eight-member crew operated virtually without paper.

While the nearby Mission Control building received electrical power from the local utility, the biosphere itself used power generated from natural gas at a separate energy center. The center produced enough energy to heat and cool the biosphere and even to sell some excess power to the utility company. Moreover, project officials report that the Biospherians recycled 100 percent of the human and domestic animal wastes and 100 percent of the water in their environment.

Computer support. More than 1,000 sensors are distributed throughout Biosphere II to monitor its complex ecosystems. Each sensor takes about 360 readings an hour. To gather and process all of the data, Space Biosphere Ventures and Hewlett-Packard developed an information system with built-in decision nodes that trigger appropriate actions when measurements fall outside expected ranges.