The computer for the 21st Century
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The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.

Consider writing, perhaps the first information technology: The ability to capture a symbolic representation of spoken language for long-term storage freed information from the limits of individual memory. Today this technology is ubiquitous in industrialized countries. Not only do books, magazines and newspapers convey written information, but so do street signs, billboards, shop signs and even graffiti. Candy wrappers are covered in writing. The constant background presence of these products of "literacy technology" does not require active attention, but the information to be conveyed is ready for use at a glance. It is difficult to imagine modern life otherwise.

Silicon-based information technology, in contrast, is far from having become part of the environment. More than 50 million personal computers have been sold, and nonetheless, the computer remains largely in a world of its own. It is approachable only through complex jargon that has nothing to do with the tasks for which people actually use computers. The state of the art is perhaps analogous to the period when scribes had to know as much about making ink or baking clay as they did about writing.

[…] My colleagues and I at PARC think that the idea of a "personal" computer itself is misplaced, and that the vision of laptop machines, dynabooks and "knowledge navigators" is only a transitional step toward achieving the real potential of information technology. Such machines cannot truly make computing an integral, invisible part of the way people live their lives. Therefore, we are trying to conceive a new way of thinking about computers in the world, one that takes into account the natural human environment and allows the computers themselves to vanish into the background.

The idea of integrating computers seamlessly into the world at large runs counter to a number of present-day trends. "Ubiquitous computing" in this context does not just mean computers that can be carried to the beach, jungle or airport. Even the most powerful notebook computer, with access to a worldwide information network, still focuses attention on a single box. By analogy to writing, carrying a super-laptop is like owning just one very important book. Customizing this book, even writing millions of other books, does not begin to capture the real power of literacy. Furthermore, although ubiquitous computers may employ sound and video in addition to text and graphics, that does not make them "multimedia computers." Today's multimedia machine makes the computer screen into a demanding focus of attention rather than allowing it to fade into the background.

Perhaps most diametrically opposed to our vision is the notion of "virtual reality," which attempts to make a world inside the computer. Users don (synonymous?) special goggles that project an artificial scene on their eyes; they wear gloves or even body suits that sense their motions and gestures so that they can move about and manipulate virtual objects. Although it may have its purpose in allowing people to explore realms otherwise inaccessible -- the insides of cells, the surfaces of distant planets, the information web of complex databases -- virtual reality is only a map, not a territory. It excludes desks, offices, other people not wearing goggles and body suits, weather, grass, trees, walks, chance encounters and in general the infinite richness of the universe. Virtual reality focuses an enormous apparatus on simulating the world rather than on invisibly enhancing the world that already exists.

Indeed, the opposition between the notion of virtual reality and ubiquitous, invisible computing is so strong that some of us use the term "embodied virtuality" to refer to the process of drawing computers out (…ing + out/in) of their electronic shells. The "virtuality" of computer-readable data -- all the different ways in which it can be altered, processed and analyzed -- is brought into the physical world.
How do technologies disappear into the background? The vanishing of electric motors may serve as an instructive example: At the turn of the century, a typical workshop or factory contained a single engine that drove dozens or hundreds of different machines through a system of shafts and pulleys. Cheap, small, efficient electric motors made it possible first to give each machine or tool its own source of motive force, then to put many motors into a single machine.

Most of the computers that participate in embodied virtuality will be invisible in fact as well as in metaphor. Already computers in light switches, thermostats, stereos and ovens help to activate the world. These machines and more will be interconnected in a ubiquitous network. As computer scientists, however, my colleagues and I have focused on devices that transmit and display information more directly. We have found two issues of crucial importance: location and scale. Little is more basic to human perception than physical juxtaposition, and so ubiquitous computers must know where they are. (Today's computers, in contrast, have no idea of their location and surroundings.) If a computer merely knows what room it is in, it can adapt its behavior in significant ways without requiring even a hint of artificial intelligence.

Ubiquitous computers will also come in different sizes, each suited to a particular task. My colleagues and I have built what we call tabs, pads and boards: inch-scale machines that approximate active Post-It notes, foot-scale ones that behave something like a sheet of paper (or a book or a magazine), and yard-scale displays that are the equivalent of a blackboard or bulletin board.

How many tabs, pads, and board-sized writing and display surfaces are there in a typical room? Look around you: at the inch scale include wall notes, titles on book spines, labels on controls, thermostats and clocks, as well as small pieces of paper. Depending upon the room, you may see more than a hundred tabs, ten or twenty pads, and one or two boards. This leads to our goals for initially deploying the hardware of embodied virtuality: hundreds of computers per room.

The technology required for ubiquitous computing comes in three parts: cheap, low-power computers that include equally convenient displays, a network that ties them all together, and software systems implementing ubiquitous applications. Current trends suggest that the first requirement will easily be met. Flat-panel displays containing 640x480 black-and-white pixels are now common. This is the standard size for PC's and is also about right for television. As long as laptop, palmtop and notebook computers continue to grow in popularity, display prices will fall, and resolution and quality will rise. By the end of the decade, a 1000x800-pixel high-contrast display will be a fraction of a centimeter thick and weigh perhaps 100 grams. A small battery will provide several days of continuous use.

Although processors and displays should be capable of offering ubiquitous computing by the end of the decade, trends in software and network technology are more problematic. Software systems today barely take any advantage of the computer network. Trends in "distributed computing" are to make networks appear like disks, memory, or other non-networked devices, rather than to exploit the unique capabilities of physical dispersion. The challenges show up in the design of operating systems and window systems.

In addition to showing some of the ways that computers can find their way invisibly into people's lives, this speculation points up some of the social issues that embodied virtuality will engender. Perhaps key among them is privacy: hundreds of computers in every room, all capable of sensing people near them and linked by high-speed networks, have the potential to make totalitarianism up to now seem like sheerest anarchy. Just as a workstation on a local-area network can be programmed to intercept messages meant for others, a single rogue tab in a room could potentially record everything that happened there.

Even today, although active badges and self-writing appointment diaries offer all kinds of convenience, in the wrong hands their information could be stifling. Not only corporate superiors or underlings, but overzealous government officials and even marketing firms could make unpleasant use of the same information that makes invisible computers so convenient. Fortunately, cryptographic techniques already exist to secure messages from one ubiquitous computer to another and to safeguard private information stored in networked systems. If designed into systems from the outset, these techniques can ensure that private data does not become public. A well-implemented version of ubiquitous computing could even afford better privacy protection than exists today. For example, schemes based on "digital pseudonyms" could eliminate the need to give out items of personal information that are routinely entrusted to the wires today, such as credit card number, social security number and address.

Jim Morris of Mellon University has proposed an appealing general method for approaching these issues: build computer systems to have the same privacy safeguards as the real world, but no more, so that ethical conventions will apply regardless of setting. In the physical world, for example, burglars can break through a locked door, but they leave evidence in doing so. Computers built according to Morris's rule would not attempt to be utterly proof against cracker, but they would be impossible to enter without leaving the digital equivalent of fingerprints.

By pushing computers into the background, embodied virtuality will make individuals more aware of the people on the other ends of their computer links. This development carries the potential to reverse the unhealthy centripetal forces that conventional personal computers have introduced into life and the workplace. Even today, people holed up in windowless offices before glowing computer screens may not see their fellows for the better part of each day. And in virtual reality, the outside world and all its inhabitant effectively ceases to exist.

Ubiquitous computers, in contrast, reside in the human world and pose no barrier to personal interactions. If anything, the transparent connections that they offer between different locations and times may tend to bring communities closer together.

Sociologically, ubiquitous computing may mean the decline of the computer addict. In the 1910's and 1920's many people "hacked" on crystal sets to take advantage of the new high tech world of radio. Now crystal-and-cat's whisker receivers are rare, because radios are ubiquitous. In addition, embodied virtuality will bring computers to the presidents of industries and countries for nearly the first time. Computer access will penetrate all groups in society. Most important, ubiquitous computers will help overcome the problem of information overload. There is more information available at our fingertips during a walk in the woods than in any computer system, yet people find a walk among trees relaxing and computers frustrating. Machines that fit the human environment, instead of forcing humans to enter theirs, will make using a computer as refreshing as taking a walk in the woods.