e-topia

"URBAN LIFE, JIM—BUT NOT AS WE KNOW IT"

WILLIAM J. MITCHELL

e-topia

"Urban Life, Jim—But not as We Know it"

William J. Mitchell

THE MIT PRESS / CAMBRIDGE, MA / LONDON, ENGLAND

Contents

For Emily and Jane

Prologue: Urban Requiem

Marshall McLuhan, 1967: "The city no longer exists, except as a cultural ghost for tourists." [1]

Yes, yes, I know; it's a familiar trope—death of God, death of the subject, death of the author, death of the drive-in, end of history, exhaustion of science, whatever. But he turned out to be right—though a few decades ahead of his time, as usual.

It's finally flatlining. The city—as understood by urban theorists from Plato and Aristotle to Lewis Mumford and Jane Jacobs—can no longer hang together and function as it could in earlier times.[2] It's due to bits; they've done it in. Traditional urban patterns cannot coexist with cyberspace.

But long live the new, network-mediated metropolis of the digital electronic era.

The First Mourner's Eulogy

DOA at Y2K! Whatever happened to the city as we know it?

I'll tell the tale.

Long ago, there was a desert village with a well at its center. The houses clustered within the distance that a jar of water could comfortably be carried. In the cool of the evening the people came to the well to collect the next day's supply of water, and they lingered there to exchange gossip and conduct business with one another. The well supplied a scarce and necessary resource, and in doing so also became the social center-the gathering place that held the community together.

Then the piped water supply came. Who could deny the practical advantages? It was more convenient, and kids no longer got cholera. Population grew, and the village expanded into a large town, since houses could be supplied with water wherever the pipes could run.

Dwellings no longer had to concentrate themselves in the old center. And the people ceased to gather at the well, since they could get water anytime, anyplace. So the space around the wellhead lost its ancient communal function, and the people invented some new, more up-to-date and specialized sites for socializing-a piazza, a market, and a cafe.

History replays-this time because the information supply system has changed. Once, we had to go places to do things; we went to work, we went home, we went to the theater, we went to conferences, we went to the local bar-and sometimes we just went out. Now we have pipes for bits-high-capacity digital networks to deliver information whenever and wherever we want it. These allow us to do many things without going anywhere. So the old gathering places no longer attract us. Organizations fragment and disperse. Urban centers cannot hold. Public life seems to be slipping away.

Take something as simple but telling as a day at the races. Before telecommunications, this involved traveling to the racecourse, mixing with punters in the stands, placing your bets with bookies on the rails, watching the horses with your own eyes, and settling your wagers face to face. Then, when radio and the telephone came along, races were broadcast, off-track betting (both legal and illegal) flourished, and on race days you could hang out at different places-at pubs and betting shops. Now, the ever-entrepreneurial Hong Kong Jockey Club has reconfigured the system once again by introducing handheld, electronic, networked devices that allow you to place your bets from anywhere in the city, at any time of day. You just need a telephone jack or a wireless connection to log in, and the system settles your accounts automatically. It is extraordinarily efficient, but it also eliminates occasions that going to the track had provided for making contacts, socializing, building trust, and doing deals.

Once again, we need to innovate-to reinvent public places, towns, and cities for the twenty-first century.

The Second Mourner's Eulogy

And that's not all. Digital communication also remakes the traditional rhythms of daily life.

Not so long ago, a family of the North lived in a fine clapboard house. There was a chimney at the heart of it, and to keep in the warmth the walls formed a simple surrounding box. In the winter, family members gathered round the fireplace-which was the only source of heat and light. Here, the

children studied, the parents exchanged news of the day, and Grandma worked at her embroidery. The hearth held the extended family together.

Then pipes for delivering energy were put in-electrical wiring and central heating ducts. Family members could be warm and have light to read by everywhere. The fire was no longer kindled, except as a kind of nostalgic entertainment on festive occasions. The kids withdrew to their rooms to do their homework and listen to their stereos. The parents began to work different shifts, and would leave testy notes for each other on the refrigerator door. Grandma got bored and cranky, and soon moved out to an air-conditioned nursing home near Phoenix where she could play bingo with her similarly sidelined cronies. The fireside circle could no longer serve as social glue.

Informatization is following hard on the heels of electrification, with social consequences that are at least as profound. As the engineers figure out the technology, and the venture capitalists keep the IPOs popping, tiny telecommunications and information-processing devices are becoming as commonplace as lightbulbs and electric motors. You can call just about anyone, anywhere in the world, at any moment, from your digital cell phone. You can have twenty-four-hour news delivered digitally, by satellite, to your hotel room TV. You can pick up your email, whenever you want it, at any telephone jack. You can get cash at any ATM, any time. Your domestic appliances have embedded processors, and will increasingly require network connections as well as electrical and plumbing hookups. Your car is crammed with sophisticated electronics, and the guy who fixes it needs a computer as well as a wrench. The early industrial age of dumb devices is over; things now tirelessly, twenty-four/seven, think and link.

Today, ubiquitously present telecommunications networks, smart machines, and intelligent buildings combine with water supply and waste removal, energy distribution, and transportation systems to create a wherever, whenever, globally interlinked world. The old social fabric-tied together by enforced commonalties of location and schedule-no longer coheres.

What shall replace it?

The Third Mourner's Eulogy.

Once, the Buddha sat under a bo tree. Disciples gathered in the shade and listened to his voice. To learn, they had to come within earshot. And in that place they formed their community of believers.

There was no other way.

Then his words were written down. First, the laboriously hand-written holy books were kept in monastery libraries, where the faithful could come to read; long after he was dead, they could travel to these book-centered communities as their predecessors had once come to the bo tree. Later, the books were printed, and the word could be delivered worldwide, to anyone who sought it. It was the same with other faiths. Though journeying to the holy sites survived as a spiritual exercise, and places like Santiago de Compostela and Mecca retained their magnetism, pilgrimage lost its more directly practical function.

As printed books proliferated and literacy spread, elaborate systems for storage and distribution of texts-both sacred and secular-sprang up everywhere. These took many scales and forms; there were national libraries, monastery libraries, university libraries, subscription libraries, municipal free libraries, suburban branch libraries, Carnegie libraries, Christian Science reading rooms, book-lined studies, book clubs, and bookmobiles. Main Streets had their bookstores and newsstands. Waiting rooms had their stacks of dog-eared magazines. Businesses depended on orders, ledgers, and invoices. Offices overflowed with files, briefcases were stuffed with paperwork, and even pockets held notes, cards, photographs, and paper money. Mail systems moved all this ink-on-cellulose around. Information was mobilized, and access to it was decentralized.

Today, text and images float free even from paper, and are pumped around at amazing speed through computer networks. We have online databases, Web sites, FAQs, and search engines. Email is rapidly replacing snail mail. In our technological age, seekers of enlightenment no longer need to embark on wearisome trips to distant sources of information. They don't even have to go to their local libraries. Bookstores, newsstands, magazine racks, theaters, temples, and churches-even bo trees-have their virtual equivalents. Students surf into electronic encyclopedias. Professors put their lecture notes

up on the Web. Retailers put catalogs and order forms online. Stock markets speed quotes electronically to the screens of traders.

Mindwork no longer demands legwork. Commerce isn't impeded by distance. Community doesn't have to depend on propinquity. Links among people are formed in hitherto unimaginable ways.

Perhaps this new social glue can be turned to our advantage. Maybe homes and workplaces, transportation systems, and the emerging digital telecommunications infrastructure can be reconnected and reorganized to create fresh urban relationships, processes, and patterns that have the social and cultural qualities we seek for the twenty-first century. Maybe there's another way-a graceful, sustainable, and liberating one.

Two tentative cheers for the global village!

Mondo 2K+

How will it all play out? And what is to be done?

The buildings, neighborhoods, towns, and cities that emerge from the unfolding digital revolution will retain much of what is familiar to us today. But superimposed on the residues and remnants of the past, like the newer neural structures over that old lizard brain of ours, will be a global construction of high-speed telecommunications links, smart places, and increasingly indispensable software.

This latest layer will shift the functions and values of existing urban elements, and radically remake their relationships. The resulting new urban tissues will be characterized by live/work dwellings, twenty-four-hour neighborhoods, loose-knit, far-flung configurations of electronically mediated meeting places, flexible, decentralized production, marketing and distribution systems, and electronically summoned and delivered services. This will redefine the intellectual and professional agenda of architects, urban designers, and others who care about the spaces and places in which we spend our daily lives.

Doing Your Bit

This new agenda separates itself naturally into several distinct levels—the subjects of following chapters. We must put in the necessary digital telecommunications *infrastructure,* create innovative *smart places* from electronic hardware as well as traditional architectural elements, and develop the *software* that activates those places and makes them useful. Finally, we must imagine the architectural, neighborhood, urban, and regional *spatial configurations* that will be sustainable and will make economic, social, and cultural sense in an electronically interconnected and shrunken world—a world in which distance has lost some of its old sting, but also much of its capacity to keep challenges and threats comfortably removed.

To pursue this agenda effectively, we must extend the definitions of architecture and urban design to encompass virtual places as well as physical ones, software as well as hardware, and interconnection by means of telecommunications links as well as by physical adjacencies and transportation systems. And we must recognize that the fundamental web of relationships among homes, workplaces, and sources of everyday supplies and services—the essential bonds that hold cities together—may now be formed in new and unorthodox ways.

It is, I suggest, a moment to reinvent urban design and development and to rethink the role of architecture. The payoffs are high, and so are the risks. But we have no choice; we cannot realistically opt out. We must learn to build e-topias—electronically serviced, globally linked cities for the dawning *début de K.*

**3
Software:
New Genius of the Place**

Watch out! As the technology of smart places matures, the metaphors are biting back.

In the early days of computer graphics, we became familiar with "virtual" objects that looked like physical ones but could perform computational tasks. We learned to "paint" with virtual brushes, store digital "documents" by dragging them to on-screen "file folders," delete by means of icons shaped as trash cans, and so on. It was as if familiar physical artifacts had been sucked up off the desktop into the PC, there to live a ghostly, magically enhanced afterlife. Now, by embedding intelligence and interconnectivity in material products and creating systems of tags and sensors, we can reverse the process. We can squirt these sorts of computational capabilities back into everyday physical things; we can get the functionality without the virtuality.

In elementary form, this is already a familiar idea; supermarket products are tagged with printed barcodes, and checkout counters are equipped with barcode readers. Dragging a product past the reader produces a computational result; software that lurks behind the surface reads the product's identifying code, looks up its price in a database, and finally adds the price to the customer's total. It may also perform important ancillary tasks, such as updating a stock inventory and collecting statistical data on buying patterns.

By generalizing this principle, we can construct spatially extended smart spaces from collections of interacting smart objects. Real desktops, rooms, and other settings—rather than their electronically constructed surrogates—can begin to function as computer interfaces. We can also create some interesting physical/virtual hybrids, as in the video arcade golf simulators where you hit a real ball with a real club, then see a simulated trajectory displayed on a video screen. As a result, our actions in physical space are closely and unobtrusively coupled with our actions in cyberspace. We become true inhabitants of electronically mediated environments rather than mere users of computational devices.

Tags and Sensors

When we want physical objects to serve in this fashion as active elements of smart places, it turns out that we must provide them with ways to identify themselves to each other. The technology may be optical, as with barcodes and readers, with fingerprint recognition systems that open doors for authorized individuals, and with face recognition systems. It may be acoustic, as with devices that emit ultrasonic signals. And it may be electromagnetic, as with ATM cards, radio frequency identification (RFID) chips in those key chain tags that activate gasoline pumps, Sensormatic shoplifting tags, and smart tollbooths that automatically identify and later bill the owners of transponder-equipped vehicles that pass through them.

It sometimes matters not only *what* things are, but also *where* they currently happen to be, so we also need ways to track the positions of physical objects—much as screen management software tracks the position of a cursor. This can be accomplished in a variety of ways. At a large scale, where accuracy to within a few meters suffices, the Global Positioning System (GPS) satellite system, together with inexpensive, miniaturized GPS receivers, can provide coordinates of vehicles and other objects anywhere on the face of the earth; this information typically feeds into onboard vehicle navigation systems and emergency service call systems. [1] At urban and architectural scales, grids of terrestrial transceivers can keep track of vehicles and cell phones. Within buildings, various pressure-sensitive and motion-sensitive, electromagnetic, optical, and acoustic sensors can follow the movements of people and artifacts —allowing calls and messages to be forwarded automatically, for example.[2] And for pinpoint accuracy at a small scale, the electromagnetic and ultrasonic techniques used in 3D digitizers can serve effectively.

Some smart objects require specialized sensing capabilities, as appropriate to their particular roles. They may be equipped, if necessary, with cameras and microphones as "eyes" and "ears." They may incorporate temperature and humidity sensors. They might watch out for tiny traces of explosives, drugs, or pollutants. There might be miniature accelerometers to detect motion, piezoelectric detectors

for forces and stresses in structural elements, micropower impulse radar (MIR) to measure distances and fuel levels, electric field sensors for capturing gestural information, [3] and digital compasses to track orientation. They might even make use of living cells as detectors for hormones and microorganisms. The list is potentially endless.

Like living organisms, smart objects will sometimes need to figure out what is going on around or within them by integrating sensory inputs from multiple sources.[4] In order to respond to a child, for example, a smart stuffed toy might sense both sound and motion. To monitor, interpret, and respond to an occupant's commands, a smart room might collect audio information from several microphones, video streams from multiple cameras, and occupant locations from a smart carpet or other position-sensing systems. This allows cross-checking of information, and eliminates many potential ambiguities.

For truly ubiquitous use, the tags and sensors embedded in manufactured products need to be tiny, robust, very inexpensive, and low-powered; as Neil Gershenfeld has observed, we need to be able to compute anywhere for pennies.[5] Here the technologists are beginning to deliver, though there is still a long way to go.[6] Video cameras, for example, are evolving into single-chip devices costing only a few dollars; they can become cheap "eyes" for almost anything. Micro-electromechanical systems (MEMS) technologies allow very small-scale sensor fabrication. And MEMS devices can become so minute that they can be powered by vibrations or solar energy, dispensing with external power supplies and batteries.

In general, new tag and sensor technologies allow objects to become aware of one another and to begin to interact. This is the first, elementary step toward artificial ecosystems and societies of smart stuff.

Embedded Intelligence

In order to process information and respond, smart artifacts need not only sensors, but also embedded memory and machine intelligence.

Although you may not have noticed if you aren't particularly alert to it, unobtrusive, onboard computers are now commonplace in vehicles, appliances, and even toys. Your automobile has sophisticated digital systems to control braking and other functions; indeed, these probably account for more of the cost than the engine and the power train combined, and they consume so much electricity that they will probably force a move from 12-volt to 42-volt batteries. Your microwave, your dishwasher, and your clothes washer incorporate more processing power than advanced computers of a few decades earlier. Television receivers and cell phones are packed with digital circuitry. Complex film-loaded cameras are giving way to digital electronic ones with almost no moving parts. Programmable card key systems are replacing mechanical locks and keys on doors. Microsoft Barney, the annoying stuffed toy spun off from the annoying kids' TV character, has a speech chip and a motion controller implanted under his purple polyester pelt. Dissect a Furby and you get an electronics lesson.

This extends a revolution in product design that has quietly been cooking since the appearance of the first microchips in the 1960s; mechanical and electromechanical subsystems account for a steadily decreasing proportion of such a product's functionality and cost, while digital electronic subsystems take up a correspondingly increasing share. By the mid-1990s, as a result, microprocessors embedded in specialized smart artifacts outnumbered personal computers by an astonishing factor of one thousand. [7]

As chips become smaller, cheaper, more capable, and more robust, and as their electric power requirements decrease, this wholesale invasion of manufactured products by digital intelligence will continue. There will be local processing power and memory available wherever it may be needed, for any purpose whatsoever. Eventually, we will cease to conceive of computers as separate devices, and begin to regard machine intelligence as a property that might be associated with just about anything.

We will increasingly inhabit a world of things that don't just *sit* there, but actually *consider* what they are supposed to be doing and choose their actions accordingly.

Instant Networking.

How can we actually configure such smart components to transform our immediate surroundings into smart spaces?

In the PC era, the answer seemed simple. You assembled computer resources in a room by plugging miscellaneous peripheral devices into a CPU box, then loading shrinkwrapped software. But this process became increasingly cumbersome as intelligent objects diversified and proliferated. All those tangled wires and blinking boxes were just too much trouble. They had to go!

An obvious first step was to replace jacks and cables with a universal short-range radio linkup among neighboring electronic devices. This could be accomplished by equipping them all with miniaturized, high-frequency, low-powered transmitters and receivers. The Bluetooth technology specification, introduced in the late 1990s by a consortium of major electronics firms, opened up this possibility by providing a workable and widely supported standard. [8] When Bluetooth devices come in close proximity, they automatically detect one another and establish a network connection.

Unfortunately, though, physical interconnection of devices does not suffice to make them *work* together. (You probably know this well if you have ever tried to hook a new printer to your PC, or connect your laptop to a conference room video projector.) You also need some simple, automatic, foolproof way to handle the hardware compatibility issues that inevitably arise. The devices have to communicate through some common digital language. Providing this lingua franca is the function of "network dial tone" software, such as Sun Microsystems' s Jini; it is designed to make all the resources of a network immediately available to any new device that links in, while simultaneously allowing that device to function as a new network resource. [9]

With wireless connection and automatic assurance of hardware compatibility, electronic devices can click together as effortlessly as Lego blocks. Networks become less like fixed plumbing and more like ad hoc furniture arrangements configured for particular, temporary purposes.

Rhizomic Software

Once a piece of smart hardware is part of a network, it can potentially download any software or connect to any network services that it may need. Thus we might imagine the capabilities of smart places being configured on the fly, as required for particular purposes—a radically new process of wide-ranging, search-engine-enabled, electronic bricollage.

In practice, some arcane but crucial issues of software style and structure need to be sorted out before this attractive idea becomes workable. In particular, it helps a great deal if code is organized not in the form of huge, monolithic systems but as collections of modular, reusable, recombinable components containing both executable statements and data; this is the underlying principle of object-oriented programming, and of languages such as C++.

Furthermore, these code components are most widely useful when they can run not only within the operating system and machine environment for which they were written, but within any computational setting. The Java software environment, for example, makes this possible by providing "virtual machines" that run on top of particular hardware and operating systems to provide uniform execution environments. [10] All this is very inefficient, but that matters little in an era of inexpensive, powerful processors and ample memory.

More radically, code to perform particular tasks may be encapsulated in the form of autonomous software *agents.*[11] Like itinerant performers, these may roam a network in search of sites to do their thing.

By the end of the 1990s, it was becoming clear to industry insiders that smart devices, ad hoc networking, and modular, relocatable software were combining to create much more flexible computational environments than those of the past. The 1960s and 1970s had been the era of centralized timesharing systems, the 1980s and early 1990s had seen client/server systems, the Internet, and the World Wide Web, but the new century would be characterized by interconnected smart stuff everywhere. University and industrial research laboratories began to flesh out the details; MIT's Media Laboratory

initiated an ambitious Things That Think project, MIT's Laboratory for Computer Science worked on a prototype technology called Oxygen, Hewlett-Packard announced its commitment to "service-centric computing," and Sun pushed Java and Jini.

Form Fetches Function

When software becomes footloose in this way, and services are there for the connecting, we can no longer expect the functions of things to be as stable and predictable as they once were. Now, a display screen on a wall might serve successively, according to our whims of the moment, as a clock, a television, a stock ticker, a portrait of a loved one, and a remote nannycam monitor. A single handheld device might play the roles of cell phone, pager, personal digital assistant, and television remote control. A simple plastic rectangle might function as a credit card, a wallet filled with digital cash, and a door key. An ATM machine (unlike an old-fashioned branch bank) might offer the services of many different banks and other financial institutions, depending upon the identities and needs of particular customers.

Nor can we expect these functions to be localized. Any smart, networked device becomes a tangible, local delivery point for an indefinitely extensible, globally distributed pool of resources and services. Some of these may be embodied as pieces of hardware somewhere, some may be accomplished by execution of software, some may be performed by actual people, and you mostly do not know or care which is which. And, if network connections are sufficiently fast, it scarcely matters whether a task is performed locally or on a processor that happens to be available on the other side of the world.

Consequently, product designers and architects face some new sorts of design quandaries. Should they build multipurpose hardware, such as multimedia personal computers, or should they create families of interacting, single-purpose devices like cell phones, digital cameras, and portable electronic books—information appliances that

fragment and disperse the functions? **12** Which capabilities of a system should be built into hardware and which should be provided by software? Which software functions should be permanently resident in a device and which should derive, as necessary, from interconnections and downloads? In the end, some affordances will derive from material structures and mechanisms, some from resident code, some from software and services sucked down a wire as needed, and some from interactions of all of these.

In the design of smart things and places, form may still follow function—but only up to a point. For the rest, function follows code. And if you need to alter these code-enabled functions, you don't rebuild, reshape, or replace material components; you just connect, fetch, and load.

Consult the Genius of the Place

Curiously enough, there is venerable precedent for these notions of embedded intelligence and sensorily aware, responsive objects and spaces. The ancient Romans believed that each particular place had its characteristic spirit—its *genius loci*—that might manifest itself, if you watched carefully for it, as a snake. They had the right idea, but not the necessary technology.

For us, equipping a place with its genius has simply become a software implementation task. Lines of code can supply every electronically augmented environment with a tailor-made, digital genius that makes its presence felt through input devices and sensors, displays, and robotic actuators. It can respond to the needs of its inhabitants, adapt to changes in its surroundings, and—by making use of its network connectivity—focus global resources on current local tasks. By virtue of the rules that it encodes, it can facilitate some activities and discourage or exclude others. It can even enforce ethical and legal norms.

Code is character. Code is the law.

4
Computers for Living In

What will smart places do for us?

They will, of course, collect and spit out information—much as computers and telecommunication devices have always done. More importantly, though, they will attend, anticipate, and respond to our daily needs in a vast variety of new ways. And they will become delivery points for a still-unimaginable range of services made available by providers scattered around the globe.

Wear Ware

Most intimately, there will be close-fitting networks of implanted, wearable, and pocket devices to attend to our most immediate, ongoing requirements for maintenance of bodily health and comfort, for self-representation and identification, and for remote communication. [1]

Our clothing and accessories will be dense with bits. There may be more lines of code in your shoe that on the disk of your current desktop PC. If this seems a bit too Buck Rogers to credit, try the experiment of emptying out your pockets, handbags, and briefcases, counting up all the objects that record, store, display, or process information in some way, and imagining their replacement by smaller, lighter, very much smarter digital equivalents. This replacement process began with watches and cell phones, and it will continue.

There is plenty of room for the necessary intelligence in footwear, belts, jackets, hats, wallets, handbags, briefcases, wrist straps, and buttons. Gloves and other close-fitting clothing can serve as gesture sensors. Tiny, lightweight CCD arrays and microphones can augment your eyes and ears. Miniature displays can be kept in pockets, strapped to wrists, and built into eyeglasses. Information can be discreetly whispered into your ear as you need it, or superimposed on a scene by means of smart eyeglasses.

You will be able to take lots of data onboard. Simple credit cards and ID cards can grow up into vastly more sophisticated smart cards with large digital memories and onboard processing power. Coins

and banknotes can be replaced by digital cash—encrypted bundles of bits securely stored somewhere on your person. Identifying and authorizing tokens—badges, business cards, driver's licenses, tickets, passports, visas, and door keys—can migrate from paper and metal to miniature digital cards, controllers, and transceiver badges.

And there will be myriad gadgets to deliver whatever specialized personal services your condition and lifestyle may require. Your health may demand prosthetic devices such as hearing aids and pacemakers, medical monitoring devices, and programmable and remotely controlled medication dispensers. If you ride a motorcycle or ski, you may need intelligent, dynamic protective devices such as inflatable neck braces. If you are a diver, pilot, firefighter, or handler of toxic materials, you may depend upon protective suits and specialized life support devices. Your more mundane daily activities may require cellular telephones, pagers, personal digital assistants, and audio and video entertainment devices. Even your jewelry may be programmed.

Body Nets.

Many of these handhelds and wearables, such as smart cards, digital wallets, and digital address books, will not require continuous network linkage; these will depend on their internal memories, and will operate in plug-in-and-load-up mode. Others, like watchband pagers, will need bursts of connectivity. Yet others, like personal radios and televisions, will receive or transmit constantly.

These electronic organs may communicate among themselves, as necessary, by means of circuitry woven unobtrusively into clothing, and connections made by buttons and snaps. They may transmit digital data (quite harmlessly) through your very flesh. [2] They may even intercommunicate indirectly via microcellular transceivers in the surrounding architectural environment.

In any case, their intercommunication capabilities will allow them to act together as a versatile and efficient system that serves

wide variety of purposes. Thus, for example, grasping a smart card with your fingers might cause your wrist device to display the amount of digital cash the card currently contains. A signal from a medical monitoring device at one location on your body might trigger release of medication at another. And you might transfer files from one bodynet to another simply by holding hands.

By the late 1990s, laboratory experimentation with wearables and bodynets had intersected with cultural theorizing of the extended and transformed body (as exemplified by the influential work of Donna Haraway), [3] with productions of body artists like Stelarc, and with the checkbooks of venture capitalists. Consumer electronics giants were experimenting with wearable digital products; Seiko, for example, put out a wristwatch wireless messager. The hopeful startup companies were appearing.[4] MIT hackers, decked out in their digital cyborg gear, were appearing in the fashion pages of the *New York Times.* And Gordon Bell was predicting: "By 2047, one can imagine a body-networked, on-board assistant—a guardian angel that can capture and retrieve everything we hear, read, and see. It could have as much processing power as its master, that is 1,000 million-million operations per second (one petaops), and a memory of 10 terabytes."[5]

You will be certain that this cyborgian stage of the digital revolution has truly arrived when breadbox-sized computer boxes mostly fade from view, and you just put on your digital devices and network connections like boxer shorts.

Appliance Intelligence

At the next scale up from wearables—that of furniture, permanent equipment, and desktop devices—your immediate surroundings will unobtrusively be imbued with electronic intelligence.

You will engage smarter and smarter boxes, vehicles, appliances, and toys to perform specialized tasks in particular contexts—ATM machines in public places for banking, point-of-sale computers for

processing retail transactions in stores and supermarkets, electronic information kiosks in transportation terminals and building lobbies, desktop devices and printers for information work in studies and offices, videoconferencing systems in meeting rooms, onboard navigation systems in vehicles, speech recognition and synthesis systems in the nursery, programmable control systems in kitchen and laundry appliances, and many more yet unimaginable.

It is useful to put this development in a very broad historical perspective. Urbanization allowed us to accumulate nonportable possessions—to populate our habitats with furniture, pictures, rugs, lamps, pianos, tableware, and all the sorts of stuff you load into a moving van when you change houses. Then mechanization took command. The industrial revolution inserted machinery into many familiar artifacts, created new mechanized products that nobody had ever dreamed of before, and produced a world that required the attention of mechanics and service technicians. Electrical networking and the proliferation of small electric motors furthered this process, ushered in the era of plug-in electric appliances, and provided our daily existence with an electromechanical middleground. Now, digital networking and small electronic processors are transforming not-so-smart appliances into very much cleverer robots.

We have gone from the writing desk to the mechanical typewriter, the electric typewriter, and finally the word processor. Cash drawers became cash registers, then point-of-sale computers. The sketchbook morphed into the film-loaded camera, then the digital camera. The craftsman's tools gave way to steam-powered and electric-powered factory machines, then to industrial robots. And the horseless carriage was the first step toward the pilotless aircraft.

Electronic Teamwork

Unlike earlier generations of computer-controlled appliances, though, future generations will rely on their communications capabilities and network connections. They will be members of electronic teams. As

in sports teams, the individual devices will have specialized roles and positions.

They will interact with smaller-scale bodynet devices, with their counterparts elsewhere in the immediate surroundings, and with larger-scale systems. This means that their affordances are not limited by the direct capabilities of their onboard hardware and software. They may suck in necessary information, as required, from distant sources. They may pump information out to remote devices that provide numerous additional functions. And they may temporarily appropriate remote memory and processing power to assist with particularly demanding tasks.

Once, for example, you snapped a baby picture, took the film to a processor, and mailed the picture to your mother. Now, you can capture the image with a digital camera, point the camera at a PC to transfer the pixels wirelessly to disk storage, immediately distribute to your entire extended family through the Internet, and leave it to them to make prints, if they like, on their home printers. You transfer bits rather than atoms, and you perform the various necessary functions at different sites from those established in the days of mechanical shutters, silver-based emulsions, and darkrooms.

Similarly, you once put a metal coin in a mechanical meter when you parked your automobile. You had to have a pocketful of change. Today, in some places, you can pay by swiping a smart card through an electronic meter. In future, the meter will probably communicate wirelessly with a transponder in your car, and automatically generate a charge for which you are billed at the end of the month. You will not need to think about it at all.

Not so long ago, when your car broke down, you had to trudge to the nearest public telephone to call the tow truck. These days, you are more likely to call from your digital cell phone. And increasingly, automobiles are being equipped with advanced computer and telecommunications systems that locate them using GPS tracking systems, automatically diagnose problems and summon service, consult computerized service records, and even allow some adjustments and repairs to be carried out remotely.

If you walked into an early-electronic-era conference room to make a presentation, you had to plug your laptop into the video projector, boot up the system, and hope that everything turned out to be compatible. Before too long, your laptop will spontaneously join the local network wherever you happen to be, and devices like video projectors and printers will simply announce themselves on the desktop and offer their services. So will the light switches, the controls for the window shades, the air conditioner temperature dial, and the video remote.

Thus the old dream of a robot-serviced future is finally materializing—but in the form of geographically distributed assemblages of diverse, highly specialized, intercommunicating intelligent artifacts, not those cadres of clanking multipurpose humanoids imagined in the late industrial era by Karel Capek * and Fritz Lang. This has evoked the usual responses to such advances in the functional range of appliances and gadgets—breathless, won't-it-be-cool scenarios of never-lift-a-finger future ease, countered by equally predictable rejoinders that it's all just a back-to-mama fantasy projected onto the latest crop of new machines.

But as in the past, both of these intellectual reflexes kick in wildly wrong directions; abundant machine intelligence is just like steel, plastic, and the electric motor—a useful addition to the designer's repertoire, to be used as appropriate, in conjunction with other materials and components, to create varied physical products that serve our needs and satisfy our desires. The cleverest, most successful designs will not parade their computational capabilities. Your cell phone, for example, internally performs some astoundingly complex operations, and carries hundreds of thousands of lines of code to provide it with the capacity to do so. Furthermore, it interacts continuously with a sophisticated surrounding environment of cellular transceivers. But all this is transparent to you. You just see that it performs a straightforward function reliably and effectively.

Buildings with Nervous Systems

These developments suggest a new evolutionary stage for architecture. Our buildings will become less like protozoa and more like us. We will continually interact with them, and increasingly think of them as robots for living in.

In the distant past, they were little more than skeleton and skin. Following the industrial revolution, they acquired elaborate mechanical physiologies—heating-ventilation-air conditioning (HVAC) systems, water supply and waste removal, electrical power and other energy systems, mechanical circulation systems, and a wide variety of safety and security systems; pretty soon, these evolved to the point where they were responsible for the bulk of a building's construction and operating costs. Today, in the wake of the digital revolution, they are getting artificial nervous systems, sensors, displays, and computer-controlled appliances; the structure becomes a chassis for the sophisticated electronic systems that play a rapidly growing role in responding to the requirements of the inhabitants.

Integration of the necessary digital telecommunications wiring raises much the same design issues as provision of electrical wiring and older forms of telephone wiring. You need vertical and horizontal distribution through some combination of walls, floors, ceilings, furniture, and special chases and trays, together with accessible junction boxes and wiring closets. And you need a system of modular jacks to provide convenient plug-in access wherever needed. But these issues loom larger since the overall amount of wiring increases dramatically, and since the pace of technological change requires flexibility and easy access everywhere.

Wireless transceivers in ceilings and elsewhere can eliminate the cables running from plugs to appliances, but they do not remove the need for a well-designed, flexible wire management system. Even if they have wireless data connections, computers and other digital devices still need electric power supply. And, since electromagnetic spectrum is a scarce resource but wired capacity can be expanded indefinitely, cables are likely to remain the most efficient means of supplying highspeed connections in densely inhabited spaces.

In the end, though, the precise character of a building's digital plumbing is a relatively unimportant technicality. What really matters is its pervasiveness—its capacity to collect and deliver bits *anywhere.*

Livables

Just as light fixtures, HVAC diffusers, and other such elements have found their natural places in architectural settings, so will the new electronic organs that a building's artificial nervous system interconnects—its sensors, displays, projection surfaces, and robotic actuators. As this evolution unfolds, the distinction between building and computer interface will effectively disappear. Inhabitation and computer interaction will be simultaneous and inseparable.

Mark Weiser's Ubiquitous Computing project, at the Xerox Palo Alto Research Center in the early 1990s, provided one of the first convincing glimpses of this possibility. **[6]** Within the interior space that Weiser created, office workers wore wireless transponder pins that allowed a computer to track their locations. The environment was populated with wearable, handheld, and part-of-the-furniture display and interaction devices. These devices were all interconnected to create a single, dispersed, interactive interface. The inhabitants became, in effect, living cursors; information that they needed automatically followed them from place to place, and showed up on whatever display device happened to be convenient at the moment. And the building always knew, from moment to moment, exactly where to forward their phone calls and their email.

Around the same time, George Fitzmaurice's spatially aware palmtop computers vividly demonstrated the potential interrelationship of wearables and livables.**[7]** These handheld devices had location and orientation sensors, and they delivered information that was relevant to current locations or nearby objects. Thus they turned whole environments into spatially organized information fields. Point your palmtop at a malfunctioning appliance, for instance, and it might identify and summon an appropriate service technician. Point it at a

product in a showroom and get technical specifications. Or point it at a museum exhibit and get catalog copy.

As designers explore these new possibilities, they will find themselves questioning old assumptions about what goes where—in particular, the traditional assignments of functions to handhelds and wearables, to the permanent elements of local settings, and to remote sites. Do you store your personal records on your body, on a computer in your house, or on a remote server? Do you keep books and records on hand, in your living room, or do you download digital versions whenever you need them? Do you sketch on a handheld surface, or on a wall-mounted electronic whiteboard? Do you control the lights and appliances in your house through traditional switches and dials mounted on the walls, through "soft" control panels on conveniently located video screens—much like the "glass" cockpits that have supplanted complex arrays of instruments in modern aircraft—or through handheld wireless devices like TV remotes?

Intelligent Resource Consumption

Smart buildings will not only be highly responsive to the needs of their inhabitants, but they will also be very intelligent consumers of resources in doing so. [8] They will be programmed to adapt themselves not just to variations in internal demands and external climatic conditions, but also to ongoing changes in the prices of the various utilities that serve them. This will allow utility companies and other suppliers to more effectively manage demand by adopting dynamic pricing strategies.

Consider electricity supply. The earliest idea was to have a large central generating plant that had a monopoly on pumping electric power out to consumers in its supply area. Simple meters sufficed to measure consumption; you got your monthly bill after the meter reader came. Then there were electricity grids, with multiple plants supplying power in different amounts, at different times, and at different prices; electric utility companies got into the business of buying

power and distributing and reselling it to consumers. Now the trend is to create highly decentralized grids with large numbers of relatively small suppliers—possibly including buildings that generate excess solar or wind power from time to time, and output it to the grid. [9] Furthermore, utility companies have long since discovered that demand fluctuates a great deal, and that it is in their interest to try to manage this by varying prices—for example, by introducing peak and off-peak rates. The market isn't so simple any more.

Under these conditions—for efficiency and equity—prices should be updated as dynamically as possible. Smart buildings should then be programmed to respond appropriately by adjusting their demands —consuming as little power as possible when prices are high, and performing intensively power-consuming tasks when prices are lowest. This is feasible because they usually have functions—such as running a home dishwasher or cooling an empty office building after a warm day—that can take place at different times and rates without causing inconvenience. So they can shop for the best times and prices. They might also be connected to multiple supply grids, and have the ability to switch among them according to current costs.

In general, smart devices and intelligent environments will be programmed to forage intelligently for the supplies and conditions that they need in order to operate. This allows creation of more sophisticated markets, leading to more efficient use of scarce resources. Gardens can be watered automatically when other demands on the water supply system are lowest. Smart cars can take account of dynamic road pricing when choosing routes.[10] Computer systems can download large files from the Internet at off-peak times. If the technical and social kinks can be worked out of the idea of metacomputing—automatically borrowing idle processors on a network to share the load of large computational tasks—we can even begin to think of the Internet as a vast computer-power grid with dynamic pricing of machine cycles.[11] Electronic intelligence, embedded everywhere, creates the necessary interfaces between producers and consumers, and allows us to rethink the ways that even the most mundane utilities are organized and run.

Fittingly, digital information itself may be the commodity most suited to dynamic utility pricing and smart foraging. The value of information often decays with time; yesterday's newspaper is not worth as much as today's, stock price information is useless if it is not timely enough, emergency medical information is ineffective if it does not arrive when needed, and any scarcity value possessed by an item of information quickly disappears as it is duplicated and distributed through a network. So dynamic pricing of network-distributed digital information, based on its timeliness and relevance in specific contexts, provides one possible solution to problems created by collapse of the "intellectual property" approach to controlling and marketing information. The idea is to charge high prices for really hot stuff, and let everything else be inexpensive or even free.

Adaptive Behavior.

Whether the operation of such smart resource-consuming systems is fully automatic, or whether it relies on displays of salient information and human attention, may turn out to be largely a matter of taste—like the choice between manual and automatic transmissions in automobiles. It may depend upon whether you enjoy driving or just want to devote your attention to something else.

One thing seems certain, though; few of us really want to program even the simplest of devices, like VCRs, microwaves, telephone answering machines, and cameras—much less our homes, offices, or classrooms. No doubt the notoriously terrible interfaces and incomprehensible instruction manuals of these devices are partially to blame for our distaste. But it is more fundamental than that. We should not have to explicitly instruct our appliances and environments at all; if they are *really* so smart, they should be able to learn what we require of them by watching us. Like the best of waiters or personal secretaries, they should be able to anticipate our needs before we are even consciously aware of them. Otherwise, these complicated gadgets are often more trouble than they are worth.

How smart, then, does a washing machine need to be? Perhaps it should automatically analyze clothing stains, mix chemicals, set the rinse and agitation cycle, and reorder supplies over the Internet. Maybe it should learn when you like to have fresh laundry ready, note the prevailing patterns of electrical power pricing, and time its operations accordingly.

What about wallboard? Maybe smart sheetrock should observe your comings and goings, automatically create predictive models of your behavior, and provide your house with the capacity to perform its environmental control chores accordingly. It might even learn to distinguish between the differing environmental needs of your teenage daughter and your aged grandmother, and to take account of who was actually at home. [12] If it got to be good enough at these games, it could satisfy your HVAC and lighting needs while cleverly minimizing energy costs. The longer you lived there, the better it would get to know you, and the better it would do.

All this becomes feasible if effective machine-learning mechanisms can be built into smart devices and places. One of the most convincing demonstrations of the possibilities, so far, is Michael Mozer's "adaptive house" in Boulder, Colorado.[13] Mozer's house (actually a retrofitted former schoolhouse) incorporates an elaborate array of sensors that monitor internal temperatures, ambient light levels, room-by-room sound and motion, the openings and closings of doors and windows, outdoor weather conditions, boiler temperature, and hot water usage. Its heating, ventilation, and lighting systems are computer-controlled. A neural network system tracks occupant movements and behavior, predicts comings and goings and room occupancies, and infers rules of operation that appropriately balance occupant comfort and energy conservation.

Reconceiving Construction

As buildings evolve in the directions represented by these new ideas and pioneering experiments, construction materials, products, and

processes will change. Steel and concrete will still be important, but they will be joined by silicon and software.

The buildings of the near future will function more and more like large computers with multiple processors, distributed memory, numerous devices to control, and network connections to take care of. They will continuously suck in information from their interiors and surroundings, and they will construct and maintain complex, dynamic information overlays delivered through miniature devices worn or held by inhabitants, screens and speakers in the walls and ceilings, and projections onto enclosing surfaces. The software to manage all this will be a crucial design concern. The operating system for your house will become as essential as the roof, and certainly far more important than the operating system for your desktop PC.

Consequently, a growing proportion of a building's construction cost will go into high-value, factory-made, electronics-loaded, software-programmed components and subsystems; a correspondingly decreasing proportion will go into on-site construction of the structure and cladding. There will be fewer discrete components, fewer complicated mechanisms, fewer moving parts to wear out and break, and much more reliance on software and solid-state circuitry to provide the necessary functions. For convenient repair, replacement, and upgrades, these sophisticated new components will need to be modular and removable; they will snap into place like the boards inside a PC, or simply plug in where required. As they become denser with wiring and electronic devices, they will become more like large-scale printed circuit boards than dumb wallboard.

Miniaturization will allow us to exploit redundancy. Instead of relying on one light fixture to illuminate a room, we might have thousands of independent pixels; it does not matter if a few burn out. And instead of providing one large fan for ventilation, we might substitute wall panels with hundreds of thumbnail-sized turbines.

These hardware and software components will become obsolete at very different rates, and repair, maintenance, and renovation strategies will have to provide for this. Simple, robust, long-life components will form a permanent chassis. Replaceable electronic devices will plug into this. Software will continually, automatically upgrade itself via

network connections. And maintenance providers will make extensive use of remote monitoring to detect problems, analyze them, and invoke service procedures as needed.

All this will mean that some new trades will appear on construction sites. Networking specialists, hardware technicians, and software hackers will increasingly join the steelworkers, concrete guys, carpenters, plasterers, painters, plumbers, tin-bashers, and electricians.

The Knee Bone Connected to the 1-bahn

Smart places, at the various scales we have now considered, nest one within the other like Chinese boxes. They form approximate hierarchies, with constant exchanges of information across the interfaces between the levels.

Think of your brain, in the near future, as a kernel surrounded by successive electronic shells. The innermost is your bodynet, which employs sensors and controls that detect small-scale gestures and subtle bodily states, together with displays, speakers, and tactile devices placed in close proximity to sensory organs, to transfer information back and forth across the carbon/silicon divide.

Your bodynet frequently finds itself situated within smart houses, hotel rooms, offices, stores, automobiles, airplane cabins, and other wired settings. Such settings are rich in connection points for your bodynet devices—either wireless transmitters and receivers or jacks for cables—and they are populated by information appliances that collect and process local information, while simultaneously importing information from the global networks. (Television receivers controlled by handheld remotes, and cordless telephones, are the humble forerunners of these information appliance systems.) Displays may be larger, speakers may be louder, and viewers and listeners may be groups as well as individuals.

Next in the hierarchy are the electronic territories of social groups such as families, companies, university communities, and professional associations. Sometimes they correspond to physical territo-

ries, as in the case of local-area networks in corporate facilities and on university campuses, but they may also be diffused over wide areas. Access to them may be controlled physically or by means of passwords, firewalls, and filters.

Finally, there are the large-scale territories of terrestrial cellular systems, the footprints of geosynchronous communications satellites, and the LEO global satellite systems. These engulf vast tracts of land and sea, and are rapidly transforming the entire surface of Spaceship Earth into one all-engulfing smart place—a global market, distribution system, and agora.

Smart Cities of the Twenty-first Century

This proliferation of nested smart places will eventually produce a new type of urban tissue, and in the end it will radically reshape our cities.

To an excellent first approximation, the places that a city contains, the activities that those places support, and the tissues that result derive their characters from the affordances of the networks that serve them. [14] By putting in sophisticated water supply and sewer networks, for example, ancient Roman engineers succeeded in creating densely packed systems of (relatively) *sanitary* places. When the industrial revolution brought gas and electric networks, cities everywhere became collections of *illuminated* places and could extend their activities around the clock—liberating themselves from the ancient bondage of the diurnal cycle. Furnaces, pipes for hot water and steam, and ducts for air enabled creation of centrally *warmed* places, and made urban life far more comfortable in cold climates. By contrast, air conditioners plugged into the power grid allowed cities like Phoenix to develop as far-flung constructions of *cooled* places—among which people shuttle in their chilled vehicles. And Alexander Graham Bell opened the way to a world of *connected* places.

Civilization has its discontents, and each of these transformations has had its downsides. Furthermore, the short-term effects have usually been to increase gaps between the privileged and the not-so; you

can be sure that the rich and powerful were always the first to get piped water supply and sanitation, electric light, efficient heating and air conditioning, and telephones. [15] But the longer-term effects of these environmental improvements have been life-enhancing, and few of us—even the most hardened technoskeptics—would want to turn the clock back.

Digital networks continue this story. We will characterize cities of the twenty-first century as systems of interlinked, interacting, silicon- and software-saturated *smart, attentive,* and *responsive* places. We will encounter them at the scales of clothing, rooms, buildings, campuses and neighborhoods, metropolitan regions, and global infrastructures.

Proceedings of SIGGRAPH 93 (New York: Association for Computing Machinery, 1993), pp. 135–142. See also T.A. DeFanti, D.J. Sandin, and C. Cruz-Neira, "A 'Room' with a 'View'," *IEEE Spectrum,* October 1993, pp. 30–33.

21 For a fast summary of research and prototype applications, circa 1996, see Larry Krumenaker, "Virtual Assembly," *MIT's Technology Review,* February/March 1997, pp. 18–19. For more detail see S. Feiner, B. MacIntyre, and D. Seligman, "Knowledge-Based Augmented Reality," *Communications of the ACM* 36, no. 7 (July 1993), pp. 53–62, and R. T. Azuma, "A Survey of Augmented Reality," *Presence* 6, no. 4 (1997), pp. 355–380.

Chapter 3
Software: New Genius of the Place

1 GPS technology is not new, but miniaturization and price reductions have been making widespread, everyday use increasingly feasible. Receivers used to be bulky devices costing tens of thousands of dollars; by the late 1990s they had become handheld consumer items selling for a few hundred dollars.

2 For pioneering applications of this idea, see Andy Harter and Andy Hopper, "A Distributed Location System for the Active Office," *IEEE Network* 8, no. 1 (1994), pp. 62–70, and Roy Want, Bill N. Schilit, Norman I.Adams, Rich Gold, Karin Petersen, David Goldberg, John R. Ellis, and Mark Weiser, "An Overview of the ParcTab Ubiquitous Computing Experiment," *IEEE Personal Communications* 2, no. 6 (1995), pp. 28–43.

3 Joe Paradiso and Neil Gershenfeld, "Musical Applications of Electric Field Sensing," *Computer Music Journal* 21, no. 2 (1997).

4 See, for example, Alex P. Pentland, "Smart Rooms," *Scientific American,* April 1996, pp. 68–76. For further details of technical approaches see Michael Coen, ed., *Intelligent Environments: Papers from the 1998 AAAI Spring Symposium,* Technical Report SS-98-02 (Menlo Park: AAAI Press, 1998).

5 Neil Gershenfeld, *When Things Start to Think* (New York: Henry Holt, 1999), pp. 152–154.

6 Paul Saffo, "Sensors:The Next Wave of Innovation," *Communications of the ACM* 40, no. 2 (February 1997), pp. 93–97.

7 This estimate is given in Ted Lewis's "Binary Critic" column, *IEEE Computer,* September 1997.

8 For details of Bluetooth, see www.bluetooth.com

9 For details of Jini, see www.sun.com/jini/ and www.jini.org. Other technologies that emerged around the same time, such as Motorola's Piano, Hewlett-

Packard's JetSend, and the HAVi specification for interoperability of home digital devices, deal with similar and related aspects of the interoperability problem.

10 For details of Java, see www.sun.com/java/.

11 Agent technologies and their applications are comprehensively surveyed in Michael N. Huhns and Munindar P. Singh, *Readings in Agents* (San Francisco: Morgan Kaufmann, 1998). A practical guide to agent development is provided in Michael Knapik and Jay Johnson, *Developing Intelligent Agents for Distributed Systems: Exploring Architecture, Technologies, and Applications (New York:* McGraw-Hill, 1998).

12 For a detailed exposition of the idea of specialized information appliances, and arguments in favor of them, see Donald A. Norman, *The Invisible Computer: Why Good Products Can Fail, the Personal Computer Is So Complex, and Information Appliances Are the Solution* (Cambridge: MIT Press, 1998).

Chapter 4
Computers for Living in

1 Some of the more interesting possibilities are described in Steve Mann, "Wearable Computing: A First Step Toward Personal Imaging," *IEEE Computer,* February 1997, pp. 25–32. See also Thad Starner and Steve Mann, "Augmented Reality through Wearable Computing," *Presence* 6, no. 4 (1997). On the antecedents of wearables and bodynets, see Chris Hables Gray, ed., *The Cyborg Handbook* (New York: Routledge, 1995).

2 T. Zimmerman, "Personal Area Networks (PAN)," *IBM Systems Journal* 35 (1996), pp. 609–618. See also Neil Gershenfeld, "Wear Ware Where," in *When Things Start to Think* (New York: Henry Holt, 1999), pp. 45–61.

3 Donna J. Haraway, *Simians, Cyborgs and Women* (New York: Routledge, 1991). See also Gray, ed., *The Cyborg Handbook,* and N. Katherine Hayles, *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics* (Chicago: University of Chicago Press, 1999).

4 Among the first were Xybernaut (which offered a head-mounted, voice-activated multimedia computer), ViA, and Teltronics.

5 Gordon Bell, "The Body Electric," *Communications of the ACM* 40, no. 2 (February 1997), pp. 31–32.

6 Mark Weiser, "The Computer for the 21st Century," *Scientific American* 265, no. 3 (1991), pp. 94–104. For more technical detail see Mark Weiser, "Some Computer Science Problems in Ubiquitous Computing," *Communications of the ACM* 36, no. 7 (July 1993).