Me++

THE CYBORG SELF AND THE NETWORKED CITY

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DOWNSIZED DRY GOODS

Even the humblest of everyday artifacts can suddenly gain utility, claim new roles, and form new spatial patterns when they are radically downsized or lightened. Ryszard Kapuscinski, for example, has pointed out the effect of the “cheap, light, plastic container” on African communities. Once, the women had to carry water in heavy clay or stone vessels on their heads. These vessels were valuable, so the women stood in line with them, for hours, at the spring. Now, plastic containers are light enough to be carried by children and inexpensive enough to be left in line while you find some shade or go off to perform other chores. Kapuscinski comments: “What a relief this is for the exhausted African woman! . . . How much more time she now has for herself, for her household!”[1]

Ironically, the affluent now also get their water in lightweight plastic containers—with labels like Evian. In this case, lightening the container helps the distributor to bypass local water supply systems and to deliver a branded product from a great distance. From the consumer’s viewpoint, lightness has a different value; it provides the product with portability, therefore adding to its appeal to travelers and recreationists. Lightness is what you make of it, in some particular context.

Since the beginning of the industrial revolution—and at an accelerating pace over the last few decades—designers have exploited new technologies to make things smaller and lighter. As they have crossed certain dematerialization thresholds, many different types of machines that were parts of the architecture have become parts of our bodies. And this has been crucial in production of the new nomadicity.

MINIATURIZED MACHINERY

Consider, for example, music storage and playback devices. Pianolas required piano movers, and pianola rolls took up a lot of shelf space. Gramophones were still bulky, but sufficiently portable to make it to the front in World War I.[2] Cassette tape players could go to the beach. The Walkman became wearable. And MP3 players have become smaller still, since they do not need to accommodate relatively bulky tapes or CDs. More and more music gets stuffed into smaller and smaller boxes. Once you might carry two or three tracks on your person; now you can carry thousands. The evolutionary path has led from heavy furniture to tabletop and desktop devices to handhelds and wearables.

As architects and product designers know, there is usually some critical subsystem that controls the size of the whole thing; get rid of it, or find some effective way to shrink it, and you can reduce overall size and weight. In structural systems, as Buckminster Fuller tirelessly pointed out, the main problem is with the compression members; find a way to replace as many of these as possible with tension members, and you get a much lighter structure. With the Diskman the difficulty was the diameter of the CD; no matter what you did, you could not make the player smaller than that—which meant you could not get it to fit in your pocket.

Furthermore, there are relationships between scale and material. It seemed natural to enclose early gramophones in wooden cabinets and to treat them as a new species of varnished furniture. As tabletop stereos emerged, the wood became increasingly residual; metal and plastic took over. And you would not dream of trying to fabricate a portable Diskman case in wood; you cannot work wood sufficiently effectively at that scale, and it does not have the right mass and strength properties. Sometimes the miniaturization of devices motivates a shift to new materials, sometimes the emergence of new materials and associated fabrication technologies enables a wave of miniaturization, and sometimes it's a combination of the two.

With cameras, the problem was film. The size of the negative controlled the dimensions of the optical system and the film transport mechanism. Shrinking film formats (and a move from glass to celluloid) accomplished a certain amount of miniaturization, but substitution of the CCD array, in digital cameras, decisively changed the rules of the game. Tiny, dense arrays allowed optical systems to shrink and completely eliminated the film transport mechanism. More subtly, substitution of electronic circuits for optical and mechanical means (particularly in the viewfinder system) changed the required connections and spatial relationships among camera parts and allowed them to be repackaged in denser and more compact ways. After a while, digital cameras were not only smaller than their predecessors, they did not look like cameras anymore—just as horseless carriages had stopped looking like carriages.

With laptop computers, you need a keyboard big enough to accommodate your fingers, fine motor skills, and a screen scaled to your visual field. Handhelds with palm-sized screens and ridiculously tiny keyboards are an uncomfortable compromise. But if you can substitute a retinal scanning display that paints a high-resolution image directly on the inside of your eyeball for the screen and a microphone hooked to a speech recognition system for the keyboard, you can shrink the whole thing to Rayban scale, and shift it from your knees to your nose.

Substitution of electronic connection (either wired or wireless) for mechanical linkages, optical mechanisms, or flows of materials also allows products to fragment and recombine. Their functions can be redistributed, in new ways, over portable devices, tabletop appliances, and fixed equipment. If you want to shrink and lighten something, you can therefore do so by offloading functions to some other location. In photography, for example, exposures have traditionally been made by handheld devices, with developing and printing operations consigned to centralized darkroom installations, and storage functions handled by albums and archives. The Polaroid instant process repackaged exposure, development, and printing into handheld devices—providing convenience at the cost of bulk. But digital photography provides almost unlimited freedom to recombine. The exposure device can be reduced to a lens and CCD array with a network connection, and it may be handheld, clipped on to another device such as a PDA or cellphone, or fixed to a wall. Images may be stored in a portable device, a desktop device, or a network server. And printers may be located wherever there is a network connection.

Sometimes, such recombinations open up new opportunities. Instant photography provided the possibility of discussing and evaluating images within the contexts in which they were produced rather than at later times and in different places. Similarly, the integration of digital cameras with cellphones provided callers with the opportunity to show what they were talking about instead of describing it verbally.

MICROFABRICATION AND MEMS

High-resolution fabrication technology provides yet another way to downsize useful devices. This has been most dramatically demonstrated in the design and production of electronic circuits. The vacuum tubes used in early computer circuitry were, unavoidably, bulky and hot. The transistors that soon replaced them were smaller and cooler and could be packed much more densely. Then semiconductor technology put the explosive exponent into Moore's Law of silicon scaling. In the 1950s, portable radios with half a dozen transistors seemed miraculous; by the turn of the century, postage-stamp-sized computer chips with 100 million transistors were commonplace.

Microfabrication typically begins with a macroscopic element, such as a wafer of silicon, and creates complex structures, such as integrated circuits, by precisely removing or depositing material. As the technology has advanced, the minimum dimensions of elements in these structures have shrunk from tens of micrometers to tens of nanometers. This progression will reach its limit when elements get down to a couple of nanometers—the size of an atom—but this is not the end of the technological line for microfabrication.[3] As the race to this limit nears its end, emphasis is shifting to invention of new types of microscale structures and systems.

Already, microfabrication techniques have been extended and generalized from electronic circuits to microfluidic systems with tiny channels, reservoirs, valves, and nozzles to replace the glass tubes and beakers of traditional chemistry laboratories, and thus allow analysis of much smaller samples. They have also been employed to produce waveguides for optical and radio signals. The name for such structures, microelectromechanical systems, is bigger than they are—so it has mercifully been shortened to MEMS.[4]

More surprisingly, MEMS can have moving parts such as switches and valves, vibrating cantilevers, and tiny gears and mechanical linkages. This enables MEMS to function as sensors that transduce some aspect of the environment into electronic data. They can, for example, serve as pressure sensors, microphones, accelerometers, and angular rate sensors. They can be employed to detect visible and infrared light. And they can become "laboratories on a chip" to detect chemical and biological agents.

Conversely, MEMS can function as actuators that transduce information into useful physical, chemical, and biological effects. They can, for example, emit light or radio frequency (RF) signals, adjust microscopic mirrors to direct signals in fiberoptic systems, and serve as motors to propel microscopic vehicles and robots.

In the early days of microfabrication, microchips usually served as the intelligence in macroscale devices. The personal computer of the 1980s defined the genre; it was a microchip, surrounded by a lot of other stuff that provided the power, and did the sensing and actuating, in a large box. Through the 1980s and 1990s, microchips were embedded in a widening array of macroscale systems, from household appliances to automobiles and aircraft. Now, as MEMS technology develops, the other stuff can often shrink as well. This is opening up new design possibilities. MEMS devices can function as insect-sized autonomous systems within the human body, and in other contexts that demand extreme miniaturization. Batch-fabricated, inexpensive MEMS can be scattered around like grains of wheat, painted onto surfaces, or mixed into materials like concrete. They can be arrayed to form intelligent skins that sense changes in their environments and respond appropriately. And they can intercommunicate and coordinate wirelessly to form systems with distributed intelligence.

THE RISE OF NANOTECHNOLOGY

Beyond micro there is nano—the world of atom-by-atom or molecule-by-molecule construction of devices and systems with key dimensions measured in billionths of a meter. The idea goes back to a famously inspiring talk by Richard Feynman, in 1959, entitled "There's Plenty of Room at the Bottom."[5] In the late 1980s, K. Eric Drexler set off a new wave of interest with his speculative book *Engines of Creation*.[6] Little more than a decade later, there was a heavily funded National Nanotechnology Initiative in the United States, and similar efforts in other parts of the world.[7] Science and technology magazines were publishing regular—sometimes breathless, sometimes critical—overviews.[8] And Michael Crichton, in his technothriller *Prey*, had seized upon the idea of nasty, self-reproducing nanoparticle swarms as a new way to scare his readers.[9]

Not only are nanoscale widgets smaller than their microscale cousins, they also behave differently. Quantum physics kicks in. Atomic forces and chemical bonds dominate. Surface-to-volume ratios are large—often yielding useful chemical and biological properties. Issues of strength and proportion, power-to-weight ratios, friction, heat dissipation, and durability and reliability tend to work out differently than they do at larger scales. You have to worry about tiny moving parts banging into relatively large air molecules. Down there at the bottom, designers must play by new rules.

In 1981, the introduction of the scanning tunneling microscope opened up the possibility of imaging and manipulating single atoms on surfaces. Since then, nanotechnologists have employed a variety of scanning microscope techniques—in particular, atomic force microscopy—to push atoms around like Lego blocks. This provides a way to handcraft interesting nanostructures, but fabrication of such structures in useful quantities has turned out to require an eclectic mix of techniques drawn from physics, chemistry, materials science, mechanical engineering, electrical engineering, and biology. At nanoscale, many of the traditional boundaries among these fields disappear.

Where microfabrication depends upon top-down imposition of patterns on material, nanoscale fabrication processes may work by bottom-up self-assembly. As in biological systems, structures are automatically built up from atomic- and molecular-scale units, then substructures are assembled into larger and more complex units, and so on. If you want to build very complex structures in this fashion, you have to find ways to minimize errors, and to correct errors automatically when they occur.

At nanoscale, the possibilities of molecular electronics and quantum computation begin to open up. Nanoelectronic circuits might be built from molecular "wires,"[10] or from quantum dots—wireless structures built up from electromagnetic "boxes" holding discrete numbers of electrons.[11] Computer memories and displays might be constructed from carbon nanotubes.[12] Complete "computational particles"—working together as amorphous computing systems—might become small enough to sprinkle like dust, float like pollen, or be injected into the bloodstream to serve as diagnostic devices.[13] And chemical and biological sensors might assay single molecules.

NEMS (nanoelectromechanical systems) might incorporate molecular moving parts. Already we see microscopic motors, gears, chains, pumps and accelerometers, bug-sized robots, and coin-sized turbines, and the Web has numerous picture galleries of designs for nanometer-scale mechanisms. Nanoscale machines can even join the wireless world. It is now possible to attach a nanocrystal antenna to an individual DNA biomolecule, so that it can be controlled remotely by radio signals.[14] It can twitch reversibly on command—to function, for example, as a tiny actuator or switch, or to change its expression within a biological system.

REFRAMING DESIGN TASKS

Extreme miniaturization is usually portrayed as a path to higher speeds, greater efficiencies, more economical use of materials, and lower costs. But it also provides a way of squeezing more functions into smaller packages, so moving them closer to the body (or even inside the skin) and freeing them from fixed locations. Sophisticated computer graphics functions, for example, first became available on terminals attached to mainframe computers, then on desktop workstations, then on portable game consoles and laptops, and now on MEMS-based retinal scanning devices. Artificial hearts began as bulky, bedside machines in hospitals, then they shrank sufficiently to become implants.[15]

In the nano era, possibilities expand further. Richard Feynman imagined putting a tiny, robotic heart surgeon inside a blood vessel, thus dispensing with surgical suites.[16] And the irrepressible Ray Kurzweil has even proposed sending billions of nanobots into the brain to replace virtual reality goggles; "If you want to be in real reality, the nanobots sit there and do nothing, but if you want to go into virtual reality, the nanobots shut down the signals coming from my real senses, replace them with the signals I would be receiving if I were in the virtual environment, and then my brain feels as if it's in the virtual environment."[17] It's like Alzheimer's, but with active, benevolent nanobots rather than passive, destructive platelets. From a network control viewpoint, it makes sense; instead of replacing signals to a couple of nodes (eyeballs) at the very edge of the neural network, go for lots of nodes at the core of the network.

This shift back to the body has also altered the context and framing of design tasks. Wall and desktop telephones, for example, have long been assimilated to the tradition of mechanical and electrical appliance design—that of clocks, toasters, coffee grinders, and stereos. Their designers are schooled in the minimalist, universalist ways of the Bauhaus and Ulm, and the most elegant exemplars find their way to the industrial design section of MoMA. But cellphones are increasingly conceived of as personal accessories—much like wallets, handbags, shoes, hats, neckties, and spectacles. It is turning out that gender, age, and status markers are important; a senior, male financial executive usually wants something that goes with his suit, while a Japanese teenage girl may prefer Hello Kitty. When phones migrate from walls and desktops to pockets, they also move into the domain of fashion design and marketing—and their forms and styles, like those of clothing, proliferate endlessly. When you begin to wear them as emblems, rather than carry them as tools, they play a different cultural role.

With computers, the shifts have been even more dramatic. Mainframes were designed as large-scale items of industrial equipment, and at their best—in the hands of Charles Eames, for example—achieved a tough, hard-edged, machine-age clarity of form.[18] They were often put on display in special, glass-enclosed rooms. The bulky computer workstations of the 1970s and 1980s were medium-scale wheeled furniture—not too different from writing desks, pianos, and treadle sewing machines, but styled for laboratory rather than domestic environments. PCs evolved from clumsy beige boxes to sleekly specialized, variously colored and shaped versions for offices, classrooms, and homes.[19] Now that they are fading into history, after a life of approximately twenty years, they look increasingly like surrealist constructions—the chance encounter of a typewriter and a television on a desktop. Portables started out mimicking luggage (right down to the handles and snaps), then appropriated the imagery of books that could open, close, and slip into a briefcase. Even smaller versions snuggled into pockets and handbags, like cigar cases, hip flasks, and makeup compacts. Next, as components became tinier, and as designers realized that parts could be interconnected flexibly rather than packed into rigid plastic or metal boxes, computers became conformable to the contours of the body. They had evolved from heavy machinery into close-fitting wearables; you could begin to imagine wiggling into them like gloves, folding them into pockets like handkerchiefs, or sporting them like neckties. Ultimately, you might think of them as smart, barely visible particles.

Once, designers separated their domains by scales and associated functional categories; circuit designers and nanotechnologists operated in the nanometer to millimeter range, product designers went from millimeters to meters, architects typically dealt with details at millimeter scale and overall building dimensions of tens or hundreds of meters, while urban designers and civil engineers might work on infrastructure and land use systems extending over many kilometers. Today, such scale chauvinism makes little sense. The solution to a given design problem might be found at any scale or combination of scales—and an increasing amount of functionality that once resided in large, immobile structures and machines is now squeezed into portable, wearable, and even molecular devices.

It makes even less sense to draw sharp distinctions between nonliving and living systems. As biology, materials science, mechanical engineering, and electronics all get down to the molecular scale, they deal with the same types and sizes of structures, and there is a growing crossover of interests and goals. As biologists engage ideas of modular recombination, splicing, and cloning, they begin to think like designers. Conversely, as designers tentatively embrace concepts of emergence, self-organization, self-assembly, and self-replication, they start to sound like biologists. Increasingly, the CAD console meets the wet lab, and the circuit shop keeps company with the chemistry bench.

MULTIFUNCTIONALITY

Growing reliance upon small-scale systems—particularly miniaturized, portable electronics—has also produced rampant hybridization of devices. Not so long ago, for example, telephones were desktop or pocket devices for audio communication, cameras were optical/mechanical/chemical devices for picture taking, and GPS navigation systems were bulky items of equipment for boats and airplanes. By about 2002, though, all of these devices could be squeezed into the same portable, electronic box—and their combination opened up a surprisingly useful new possibility; you could take a picture and instantly transmit it, along with a map of the place where the picture was taken.[20] Servers could begin to accumulate image databases—with automatic indexing by time and date, location, and author—from multiple, mobile, remote sources.

Similarly, cellphones and PDAs, which had arrived upon the scene as separate boxes, began to fuse into one.[21] This convergence was prompted, in part, by the competition for pocket and handbag space; why carry around two boxes when you can get what you need from one? And it was also motivated by the search for economies; why double up on power supplies, processors, display screens, and keyboards? But its most important consequence was the convenient integration of functions that had hitherto been separate; why keep your address book and your dial-up device in separate, disconnected boxes?

There is, however, a crucial space-time tradeoff to consider. When a device such as a Swiss Army knife or a PDA provides access to many different functions, you can only make use of one of these functions at a time, and you have to switch from mode to mode—from the knife blade to the corkscrew, for example, or from the address book to the calendar. Conversely, a spatial array of single-purpose knives, corkscrews, and so on takes up more space, but there is no time-wasting and potentially confusing mode switching, and you can store each special device in its context of use—the corkscrew near the wine rack, and so on. Where space is scarce and there is little or no fixed infrastructure to rely upon, as in a hiker's backpack, multifunctionality and form factor minimization tend to win. Where space is fairly tight, as in a tiny city apartment, multimodal devices such as sofa beds may still make sense. But where there is plenty of room and a lot of fixed infrastructure, as in a large suburban house, it is far more convenient to provide special-purpose devices in their contexts of use—beds in bedrooms, sofas in living rooms, corkscrews at bars, and knives in kitchens.

It makes a difference if you can switch modes easily; unfolding a sofa bed for sleeping is aggravating and time-consuming, but picking a function from a menu on a PDA is not so bad. Context-sensitivity, if it can be reliably achieved, is even better; a really smart portable device might know where you are and what you need to do there, and adjust its current mode accordingly.

Miniaturized, mobile devices sometimes allow us to save time by performing tasks while we are in motion. Most of us, for example, have no difficulty listening to the radio while jogging or driving. But our capacity to pay attention is limited, so driving while talking on a cellphone is riskier. When you need to use keyboards and view video screens, it is wise to stop, sit down, and give them your undivided attention. As broadband wireless connections deliver fatter streams of bits to the mobile body, attention management will become an increasingly crucial design issue. The mechanisms may be very simple, as when voicemail or TiVo allow you to defer attention to data streams until you are ready. Or they might depend upon sophisticated context-sensitivity—enabling a cellphone or automobile navigation system to interrupt you only when it is safe to do so, but to be bolder when the message is really urgent.

As devices become smaller, as software takes over more functions from hardware, and as space-time tradeoffs are critically reevaluated, traditional functional categories may no longer hold. Electronic devices may readily be assembled into unprecedented combinations that provide hitherto unavailable functional mixes. These assemblies may be stuffed into compact packages, or they may be constructed through dispersed network connections. Through wireless interconnections, these functions may be divided, in whatever ways turn out to be most convenient, between smaller, wearable devices and larger elements of immobile infrastructure. And, by virtue of their embedded electronics, objects that have long performed traditional functions—from items of clothing to sheets of wallboard—will acquire increasingly important ancillary functions.

Where efficiency matters, as in the layout of a chip, form follows function in rigorous fashion; sophisticated optimization techniques are used to minimize the distances that electrons must move through surfaces, to pack components as densely as possible onto scarce chip real estate, and to assure that heat is effectively dispersed. Conversely, at scales and speeds where the lengths of the wired or wireless linkages among standard electronic components have trivial effect upon performance, designers have enormous freedom to shape electronic assemblies into arbitrary sculptural forms, to mold them to the contours of the body, to conceal them within other objects, and so on. During the 1980s, the Department of Industrial Design at London's Royal College of Art championed this freedom, and many innovative designs for electronic products emerged—most notably, perhaps, Daniel Weil's designs for transistor radios. More recently, designers of electronic toys have exploited it in increasingly imaginative ways—dolls converse electronically, toy vehicles acquire sophisticated electronic functionality, electronic dogs and other pets learn from their environments and respond to care; Lego puts electronics into modular building blocks, and Tod Machover's *Toy Symphony* blurs the line between electronic play and performance.

BACK TO THE BODY

All this has intensified interest in the scarce real estate of skin surface and its immediate surroundings. When timepieces resided in clock towers, they competed for central urban sites, but when they shrank to watches, they began to compete for wrist space—scarcer (at least by convention) on female wrists than on male ones. When Marconi set out to build his Atlantic radio telegraph station, he first had to find an industrial-scale chunk of real estate on Cape Cod, but when we decide to carry cellphones, we have to find space in our limited pocket, belt, or handbag real estate. Topography established the context for Marconi's design; anatomy does so for a cellphone design.

Where architects have traditionally responded to human needs by allocating square footage for mechanical and electrical systems, furniture, and equipment within the rigid, large-scale fabric of buildings, cyborg couturiers are now doing so by locating miniaturized devices within the smaller-scale, more flexible fabric that clothes us.[22] The microterrain immediately surrounding our bodies is providing habitats (mostly with very limited carrying capacities) for new, electronic species, which may be classified according to their sizes and shapes (known in the trade as their form factors), their modes of attachment to the body, their degrees of conformability to the body, and their degrees of visibility. You can think of these species as electronic parasites that both depend upon their hosts and provide benefits to them. And these parasites are evolving rapidly as they compete for the available niches within this up-close-and-personal terrain.

Traditionally, these niches and species have been explored most rigorously by designers of gear for foot soldiers—who need to be as effectively equipped as possible, but who cannot be expected to lug too much weight. A Roman centurion carried around about forty-five pounds, but a modern soldier may be burdened with three times that. Not surprisingly, then, the U.S. Army has been quick to establish an Institute for Soldier Nanotechnology, focusing on "threat detection, threat neutralization (such as bullet-proof clothing), concealment, enhanced human performance, real-time automated medical treatment, and reduced logistical footprint."[23] According to the director: "This will be achieved by creating, then scaling up to commercial level, revolutionary materials and devices composed of particles or components so tiny that hundreds could fit on the period at the end of this sentence." Reversing their usual tendency, weapons systems planners are beginning to think small.

ELECTRONIC PARASITE NICHES

Some emerging, miniature electronic species find their niches—at least initially—in the strap-on, backpack systems such as the packs of hikers and foot soldiers, and the wearable equipment of scuba divers. These systems typically consist of fairly large, rigid elements linked by flexible fabric, leather, or hinges so that they can conform reasonably closely to the contours of the back. The more loosely strapped, shoulder-hung variants can accommodate smaller objects, such as cameras. This part of the terrain has a lot of carrying capacity, but it produces cumbersome, clumsy appendages (which are particularly irksome indoors and in confined spaces), so it is best avoided whenever greater miniaturization provides the opportunity.

The possibility of gripping large objects of arbitrary shape in the hand provides another attractive parasite niche. Historically, it has been occupied by the luggage of travelers, by large weapons—from spears to shotguns—or by specialized mechanical devices like portable typewriters. Generally you can only carry one or two things, so competition for this niche is intense. In the latter half of the nineteenth century, the winner was often the gentleman's walking cane, which therefore acquired an astonishing range of specialized secondary functions—weapon cane, tippling cane, pooper-scooper cane, forked cane for trapping snakes, bicycle pump cane, seat cane, gun rest cane, cigarette case cane, gas lighter cane, watch cane, spyglass cane, zither cane, flashlight cane, cologne cane, and many more.[24] Today the victor in this niche is commonly a laptop computer with a handle or carrying case—a device of high functionality that cannot easily move into smaller-scale habitats because of the need for large screens and convenient keyboards. Like the cane, it can accommodate numerous secondary functions—now provided by plug-in peripheral devices, such as DVD drives for playing movies. The principle is the same, though the form factor (driven by the primary function) is different. But the laptop's victory is a tenuous one; handheld objects are always in danger of being put down for something else.

The traditions of clothing design have established an important niche for electronic parasites that can be slipped into pockets or hung in pouches and holsters on belts. Since bulging pockets are uncomfortable, and tend not to be regarded as a fashion plus, this niche imposes severe restrictions on the length, width, and thickness of objects. And, since pockets are flexible containers that may be subject to stresses as the body moves, it is an advantage for objects competing for pocket space to be flexible, conformable, and resilient. So far, the most successful electronic invaders of pocket space have been cellphones, PDAs, and electronic cards of various kinds. Devices that can squeeze into this niche can become almost as inseparable from us as our underwear. As miniaturization reduces more electronic devices to pocket size, and as new polymer-based technologies enable flexible batteries and circuits, the competition for pocket space is likely to intensify.

Still smaller electronic parasites may be sewn to clothing like buttons, pinned on like badges, strapped on like watches, or directly attached (with or without body piercing) like finger rings, navel jewelry, and ear studs. Cameos and lockets may run video loops instead of displaying static images, and sparkle may be provided electronically rather than by the cut of a gem. At this scale, conformability and flexibility matter less; jewel-like devices can, without producing discomfort or inconvenience, be rigid and quite freely shaped. Furthermore, systems of rigid, jewel-sized elements can be connected flexibly (like strings of beads) to make much larger, conformable constructions.

Let's not forget teeth. If you have to get a gold tooth or ceramic crown, why not pack it with electronics? If your teeth carried an RFID tag, you might make purchases or open hotel room doors by flashing a smile. Maybe a memory filling would be a good, safe place for your crucial medical records. And, if you squeezed a wireless speaker into a molar, you could take advantage of the fact that your jawbone efficiently transfers sound and eliminate the earpiece of your hands-free cellphone. The generalization to nails and lashes is obvious.

And finally, of course, electronic parasites are increasingly capable of getting under your skin. Although they have been framed culturally in very different ways, the practices of body piercing and subdermal implantation are not far apart technologically. You can, for example, have a rice-grain-sized RFID chip injected by syringe to provide purchasing power and location-tracking capability.[25] Deeper within the body, we will increasingly find cochlear implants, internal defibrillators, and miniature devices incorporating sensors and transponders capable of measuring blood pressure and other conditions transmitting data wirelessly to external receivers. These devices are more permanently attached than external wearables, and you do not have to remove them to take a shower.

Some of these proliferating parasites can attach themselves wherever there is room, but others require particular anatomical contexts. Thus there are growing, highly specialized genres of miniaturized eyepieces, earpieces, mouthpieces, and even nosepieces—all of which may, on occasion, be integrated into specialized masks or helmets. Wrists are good places not only for displaying time but also for other small-screen information. Shoes can provide convenient, well-engineered housing not only for batteries but also for generators that harvest the energy of footsteps to recharge them—and maybe even for energy storage and actuators that would enable you to leap tall buildings in a single Superman bound. And complete exoskeletons, composed of nanoparticles and electroreological fluids, promise both protection and the superhero accoutrement of a stiff, high-powered "forearm karate glove."[26] Of course, you don't have to be Stan Lee to imagine Marvel Comics scenarios other than those sketched by researchers in search of military funding; imagine street protestors who could effortlessly vault over riot police, equestrian and motorcycle gear that stiffened into a protective carapace when you were thrown off, and exoskeleton extreme sports.

SMART THREADS

Since the accommodation available at any point in intradermal and near-extradermal terrain is limited, and since there are efficiencies to be gained by centralizing rather than duplicating common functions, there is a growing need for network linkages among the electronic devices distributed around and within the body. It may make practical sense, for example, to centralize power supply instead of equipping each device with its own batteries or generators. Or there may be multiple, parasitic power generators—sucking in kinetic, thermal, light, and radio frequency energy at various bodily locations—to create a miniature power supply grid. This, then, introduces the need to drape the body with power cords, or—perhaps more elegantly—to weave power distribution circuitry (maybe composed of conductive polymers) into clothing.

For data networking there are more options. The links may be wired, as with the connections between pocket telephones or music players and earphones—the wires loosely draped or running elegantly through seams or zippers. Or links may be wireless, allowing anatomical logic rather than contiguity requirements to dictate disposition of functional elements around the body—relatively bulky power supplies and processors in pockets, audio output in the ears, video displays in handhelds, on wrists, or integrated with spectacles, sensors wherever they are needed, and so on. They may even be run (harmlessly) through the body itself.

Being smartly turned out will take on a whole new meaning as clothing fibers and fabrics acquire more active functionality and become increasingly programmable.[27] They might, for example, expand to keep you warmer in cold weather, open up to provide more ventilation in hot weather, tighten and decrease porosity to become waterproof, change color on command, and stiffen to provide protection in the event of accident or attack. By incorporating microcapsules of phase-change material, fabrics might absorb energy to cool you down when you're sweaty and expel heat to warm you when you're chilly. Gloves, socks, and tights might be programmed to teach dancers and athletes by applying tactile prompts, or to diagnose injuries by detecting changes in gait. And "accessorizing" will mean adding new devices to your network.

Thread with extended functionality will open up new possibilities for the ancient crafts of weaving and embroidery. Electrically conducting thread will allow circuit embroidery. Weaves of actuating thread will allow dynamic, programmable shaping and fitting. Threads that can vary their color will open up the possibility of animated tweeds and plaids. A programmable tie, woven from smart thread, might knot itself automatically and download patterns from the Internet.

Just as portable wireless devices are connected to nearby transmission and reception points, networked bodies may become mobile subnetworks of larger networks—maybe using cellphones, wireless PDAs, or button-scale transmitters and receivers to establish the necessary external links. They may incorporate RFID tags to electronically provide information about themselves. And, since the body itself produces low-powered electromagnetic radiation, it may function as a naked network node—enabling, for example, remote wireless monitoring of heartbeats.[28] The ancient, mystical idea of the body's ineffable aura takes on, in this context, precise engineering meaning.

Some of this will probably turn out to be miscalculated science fiction, and some of it will soon seem banal, but it's the repetition of a familiar theme that matters. Before the industrial revolution, buildings were mostly big, dumb boxes; then they acquired increasingly sophisticated mechanical, electrical, telecommunication, and control systems. Now, by taking advantage of electronics and nanotechnology, the rag trade is following in the footsteps of the construction trade.

AMBULATORY ARCHITECTURE

As the functionality of small things increases, they are insinuating themselves, like resourceful ticks and fleas, into increasingly intimate spaces. The traditional roles of clothing systems—thermal protection, waterproofing, impact protection, identity signaling, and so on—are being rethought and addressed in radical new ways.[29] And the elements of clothing systems are acquiring growing repertoires of new functions.

So designers are asking themselves some new kinds of questions. What might you now put in your pockets, wear on your belt, or carry in a backpack? What sorts of functions can you fit into jewelry, and how should jewelry express these? How might underwear and implants work together? What can be fitted, and what must hang more loosely? How much useful electronics can you jam into your shoes or your hat? What should be implanted semipermanently, what should go into inner garments, and what is best accommodated in easily shed outer layers? How can electronic earpieces, eyepieces, and mouthpieces be assimilated to traditions of facial adornment? Can you make use of rings or gloves to sense finger gestures—maybe replacing keyboards? How should wearable devices respond to bodily movement, changes in surrounding conditions, and emergencies? Might programmable, animated tattoos and makeup serve your display needs? What has to be waterproof? Where should we run the bodynets, and what should we run through them?

The ongoing shift of functions from urban and architectural to bodily real estate inverts some familiar customs and rituals. You once slipped into a telephone booth to make a call (and Clark Kent did so to change his costume), but you now slip a cellphone out of your pocket. Playing music through a stereo system at a party is a social gesture, but playing it through a Walkman is a way to withdraw. In a movie theater you look for a good seat and orient your eyes to the screen; with a portable display, you sit down anywhere and arrange the screen in front of your eyes. We are evolving our manners and social conventions in response—learning to avert our eyes from our seatmate's laptop screen and responding to "no cellphone" signs as our forebears responded to "no smoking" and "no spitting."

Where walls once established relatively clear and stable boundaries among social settings, mobile devices create unexpected, and sometimes difficult-to-manage juxtapositions. When your cellphone rings, there is a potential conflict between the behavioral requirements of your current physical setting and those of your electronic environment. You might choose one over the other, thereby alienating your companion or your caller, or the parties to the call might pass the phone around to their companions, using a simple ritual to bind distant social settings temporarily together. You might also scramble social settings, to the possible discomfort of others, by taking work calls in domestic or recreational settings, or personal calls in formal work settings. And you might unconsciously let the demands of one setting dominate those of the other, making motorists wish that you would shut up and drive, lecturers wish that you would look up from your screen and listen, and callers wish that you weren't simultaneously emailing someone else.

And all this, of course, transforms the ancient logic of threat and defense; the suicide bomber, with a small but powerful explosive device strapped inconspicuously under his shirt, is dramatic testimony to that. Airport security managers have become very interested in shoes. Miniature, self-actuating weapons—from high-powered letter bombs to anthrax spores—may be sent through the mail and might even be attached to insects or nanorobots. And it no longer suffices to frisk for guns and knives; checkpoints must rely increasingly upon sophisticated electronic detection of concealed devices and tiny traces of chemicals and biological agents. The boundary is blurring between systems that render the body transparent for medical purposes, such as x-ray machines, and those that do so for security.

As miniaturization continues, and as more and more functionality migrates to the body, literally off-the-wall (and into the skin zone) design moves will cease to seem so strange. We will indeed approach the condition of "walking architecture." We will be forced to abandon the macho prejudice that soft "fashion" is frivolous, while hard "construction" is serious. The functions of flexible, mobile clothing will be tightly integrated with those of rigid, fixed infrastructure. The IEEE will meet *Vogue*, and MIT will find common ground with FIT; the subtle skills of the clothing designer will be drawn together with those of the electronics engineer and the nanotechnologist to redefine radically the role of the first few millimeters surrounding our perspiring biological perimeters.

8

FOOTLOOSE FABRICATION

We produce the artifacts we want by bringing together designs, energy, and materials—all of which may be delivered to the production site, from a distance, through networks. When you bake a cake in your kitchen, for example, you follow a recipe that may have arrived through the mail, you apply thermal energy that was most likely supplied in the form of piped gas, and you combine ingredients transported from around the world through a variety of transportation networks. When you laser-print a piece of artwork in your office, the design arrives over a computer network, the electricity to activate the print mechanism is supplied by the grid, and the paper and toner cartridges (the weak link in this web) probably arrived by truck.

Very few artifacts are produced directly, at one location, from natural raw materials. Most are in fact put together from other artifacts; in other words, they emerge, through multistep processes, from supply networks. The nodes of these networks are sites at which materials are organized, according to some design, through the controlled application of energy. Today—notably, for example, in the fabrication and assembly of electronic components—these networks may extend globally, and production usually requires careful timing and coordination of parallel activities at multiple sites.

In the era of craft production, multiple fabrication and assembly tasks were performed sequentially, at one location, in the craftsman's shop—a strategy celebrated, for example, by William Morris. Industrialization sought the advantages of division of labor, specialization, and parallel processes; industrial assembly lines form transportation networks linking sites of specialized tasks. In today's network era, enhanced transportation and telecommunication capabilities allow greater spatial division of labor and, in effect, the expansion of assembly lines from factory to global scale. If you are a twenty-first-century producer, you don't just manage plants, you manage complex supply networks.

DECENTRALIZED PRODUCTION

When the machines that bring designs, energy, and materials together at nodes in supply networks are bulky, heavy, and expensive (as with high-speed printing presses and CD burners), there are few of them, and their locations tend to be fixed. They are potential bottlenecks in the flow of production. Furthermore, as robber-baron capitalists and Marxist revolutionaries knew equally well, they provide opportunities to acquire political power by grabbing the means of production. But when miniaturization allows the development and proliferation of small, inexpensive production devices (such as laser printers), redundancy can be introduced into supply networks. Production can often be decentralized and even mobilized. Under these conditions, political power can be distributed (and centralized power can be subverted) by producing such devices in quantity and spreading them around.

Consider, for example, the evolution of the supply networks through which the humble ice cube cometh. The frozen water trade began, on a large scale, with the harvesting of big blocks of ice from New England lakes and rivers by means of ice plows.[1] Increasingly efficient long-distance bulk transportation networks made this possible. Blocks were stored in huge icehouses near the rural harvest points, transported by sailing ship to cities as distant as Calcutta, stored again in urban icehouses, and eventually distributed by ice cart to domestic iceboxes. By the 1880s large, steam-driven artificial ice plants were becoming competitive—particularly in warm locations far from the sources of natural ice; these depended upon water supply, energy supply, and local delivery networks, and they were a first step in decentralization of ice production. Then came electric supply networks, small electric motors, the invention of sealed-container refrigeration, and mass-produced domestic refrigerators. Ice production had been a centralized industrial activity, but by the 1950s it had fragmented and recombined with domestic space. Today small, automated ice-makers are nodes in domestic electrical and plumbing networks, and bite-sized ice cubes pop out of your refrigerator door; the distance from production point to your glass has shortened from thousands of kilometers to a few centimeters.

Limits on network capacity, costs of transporting things through networks, and the losses incurred in transportation also play roles in establishing the relative advantages of centralized and decentralized production. Steelworks are often concentrated near sources of iron ore and coal, for example, since it is more expensive to transport these commodities over long distances than to transport the less bulky finished products. Ice plants were located near ice markets, since ice gradually melted during transportation. And the mills of the early industrial era were clustered around sites of water or steam power, since production machines had to be within range of the belts and other mechanical means that were used for transmitting power. But when the crucial networks become ubiquitous and efficient, as with modern electrical grids and the Internet, the importance of distance correspondingly diminishes; it hardly matters where you plug in a PC to download and print a document from a Web server.

These effects are most pronounced, and perhaps most threatening to established industries, when mobilized, easily replicable software transforms large numbers of Internet nodes into a highly redundant, geographically dispersed, production and distribution system. Thus when music industry lawyers tried to shut down the KaZaA peer-to-peer file-sharing system, they found that the developers were living in the Netherlands, the programmers were in Estonia, the location of the source code was unknown, the distributor was based in Australia but incorporated in Vanuatu, and installations were scattered over 60 million Internet users in 150 countries.[2] In the long run, the established music industry had about as much chance as the New England ice harvesters.

PERSONALIZED PRODUCTION

Traditionally, industrial production has sought scale economies. To compete effectively, industrialists built big, fast machines that turned out long runs of standard products at the lowest possible cost. (The higher the investments in this machinery, the more intensively it had to be used.) But decentralized, personal production is more concerned with personalization—that is, with smaller runs of products that may be more expensive but are more precisely adapted to the specific requirements of particular contexts. It is the difference between a high-speed newspaper press and your personal laser printer.

You can provide for customization by equipping a production device with lots of knobs and dials. A really good manual camera, for example, is festooned with gadgets you can adjust and set, and provides a photographer with extraordinary control of the subtle qualities of images. A point-and-shoot camera, by contrast, efficiently produces a highly standardized product and, since it doesn't have to provide so many external control points, is usually a smaller, cleaner, and simpler-looking object.

As production devices have acquired embedded intelligence, a new possibility has emerged; you can control (or hack) them by sending them streams of bits. So your laser printer can produce different pages, and your MP3 player can produce different sounds, depending upon the digital input. At another level, if you have the programming skills, you can mess with the resident code that interprets such input—so altering the types of products that are output.

At more industrial scales, numerically controlled (NC) production machinery has gradually been taking over from older, more cumbersome, manually controlled devices. At first, NC machinery was driven by paper tape; now it is run directly by computers. The shift to NC reduces setup costs and the need for close manual control and so allows production of varied output without crippling cost penalties. Thus a numerically controlled laser cutter can efficiently produce highly varied shapes from sheet material, and a numerically controlled deposition printer can produce three-dimensional solids. By the 1990s this shift was vividly being reflected in architecture; buildings like Frank Gehry's Guggenheim Museum in Bilbao were no longer constructed from the simple, repeating components that had characterized construction in the industrial era, but from complex, CAD/CAM-fabricated, nonrepeating elements.[3]

CUSTOMIZED PRODUCTION AT A DISTANCE

As inexpensive, digitally controlled production devices have been networked, it has become possible to download designs from distant servers, maybe tweak and customize them as required, then produce them locally. So increasingly it makes sense to distribute designs through telecommunication networks rather than finished products through transportation networks and to produce customized physical artifacts on demand, wherever and whenever they might be needed.

Fax machines provided an early, modest intimation of this new logic of decentralized, customized, production at a distance. At the transmission end they begin by harvesting text and images—the graphic design that is to be reproduced at a distance—from paper sheets. They encode and send this information electronically, at high speed. At the reception end, they reinscribe it on new paper sheets.

When you fax a document you don't *actually* perform the miracle of teleporting a sheet of printed paper, but the effect is the same. A good Platonist would know just how to describe the process. You separate an object's form from its material, transmit the dematerialized form, and eventually reembody the form with new but indistinguishable material. You dematerialize, then rematerialize. You keep the bits constant, but substitute new atoms.

Even more dramatically, since laser printers have become commonplace, vast quantities of textual and graphic material are now stored on servers, downloaded anywhere there is a network connection, and printed out on demand. The distribution system for printed documents has, in effect, bifurcated; instead of printing documents at a central location then distributing information and paper bonded together, the idea is to distribute blank paper and ink as inexpensive commodities and to distribute information separately via highly efficient electronic channels. In many contexts, particularly where the numbers of copies are small or the information is frequently updated, the efficiencies of this distribution strategy far outweigh the economies of scale realized through centralized high-speed printing.

This has, of course, crucial implications for publishers, book retailers, and libraries. Ever since the industrial revolution gave us high-speed presses, books have been produced in bulk at central factory locations, stored (at high cost) in warehouses, distributed to retailers who store them again on their shelves, and finally delivered to libraries and consumers. This system makes it expensive and difficult to keep titles in print for long periods and to distribute books effectively to remote corners of the world. Furthermore, lots of books are distributed to retailers only to remain unsold, eventually to be returned to the publishers and pulped. Now, however, it is feasible to store books in electronic form on servers rather than in print form in warehouses, to download them on demand to point-of-sale book machines, and to print and bind them on the spot.[4]

And the potential of new print technology does not end there. At MIT's Media Laboratory, Joe Jacobson and his research group have prototyped the idea of a "desktop fab."[5] The idea is to print logic chips, electronic tags, MEMS devices, and the like on inexpensive substrates such as paper or plastic using "ink" consisting of nanometer-sized particles. Instead of purchasing standard electronic components that were produced in billion-dollar specialized facilities, you might download and print your own—much as you now download software.

A NEW LOGIC OF PRODUCTION

As a result of decentralized, customized, production at a distance, supply networks are destabilized and transformed, and they demand rethinking. From an economist's perspective, for example, a chain through a supply network progressively adds value to materials—going, for example, from water to ice cube, sand to a silicon chip, or electronic components to fully assembled computer. Traditionally, the sequence has been one of design, component fabrication, assembly, warehousing, retailing, and eventually disposal or recycling. Now the producer's crucial assets may be designs residing on servers rather than completed products in warehouses, and these designs may be applied to add value to materials at multiple, decentralized production points of fluid and often indeterminate location, rather than at fixed, centralized industrial sites.

From a designer's perspective, the process is one of progressively binding design decisions to materials. At each stage, designers are constrained by the ways in which variables were bound at earlier stages. Thus if I assemble a design out of Lego blocks, I am constrained by the predefined geometry of my components; if I assemble an electronic system out of standard chips, I am constrained by the earlier decisions of circuit designers; and if I assemble an order for personalized sneakers online, I work within a tightly bounded range of sneaker features and their combinations.[6] But we are now moving from early binding of design variables to late binding. As a designer working with a networked, digitally controlled production device, I can select the design to download and customize it to my circumstances by choosing values for parameters at the very last moment before impressing it upon materials.

It matters little whether the digital master files that increasingly control decentralized production of material and acoustic artifacts are generated by processes of scanning, recording, and otherwise capturing existing physical reality, whether they are constructed directly by means of text, music, or CAD editing software, or whether they are complex hybrids. In a digitally controlled world, Nelson Goodman's hitherto telling distinction between autographic and allographic production collapses. Every artifact has a digital script, score, or plan, and every production process is an automated performance. Creation of the script, score, or plan may look like composition (taking place in meticulous, step-by-step fashion, using some sort of editing software) or more like recording a performance—with the operations executed at high speed, using specialized instruments and interfaces.

And this produces a curious new category of art objects. Under conditions of craft production, art objects are unique. We value their direct connection to the hand of the artist, and we care about provenance; they possess the quality that Walter Benjamin famously termed "aura."[7] Under conditions of mechanical reproduction, there is a distinction between an original (an oil painting by Vermeer, for example) and its copies, such as the postcards for sale in the museum store—a mass audience consumes these aura-challenged, industrially produced commodities. But under conditions of materialization on demand from a digital file, there need be no original; new material instances may be produced at any time, and instances may differ widely from one another—for example, by being produced at different scales, at different resolutions, or with different materials.

MUTABILITY, RECOMBINATION, AND NAPSTERIZATION

The shift to decentralized, digitally mastered production is inexorably eroding structures of authority that had been sustained by mutually supportive strategies of productizing intellectual and artistic work, industrializing mass production, and legally controlling replication processes. The debate buzzing around this transformation has mostly been cast in terms of ownership of intellectual property, payment, copying, and reuse rights.[8] It has pitted the aggressive lawyers of large entertainment and publishing companies against libraries, academics, and defenders of the public interest in the areas of fair use and unrestricted access. But maybe even more fundamentally, the debate is also about preserving the stability, identity, and closure of intellectual products versus the possibility of creative transformation and recombination.

If you purchase a CD from a record store, for example, you get the set of performances that the record producer has chosen to bundle together—no more, no less—whether you want them all or not. But if you rip all your CDs, and store the MP3s on your hard drive, you can group and sequence performances in any way you want.[9] And if you download MP3s from Napster or one of its successors, you gain even more freedom.

This breaks down the unity of the CD while preserving the integrity of recorded performances, but the musical strategy of sampling takes the process a step further. The sampler employs digital editing technology to appropriate fragments of musical material from multiple sources, transform them, and recombine them to produce new works. This is an innovative and artistically vital practice but, under the usual rules of industrial-era copyright, it is treading on dangerous legal ground. Artists get away with it only so long as the appropriated fragments are not copyrighted by aggressive holders, not overly large, and not too recognizable after transformation. If their compositions turn out to be profitable enough to make it worthwhile, they are likely to find themselves pursued by IP sharks.

Print publishers, like record companies bundling tracks on CDs, have traditionally grouped texts into issues of magazines and journals and into bound hardback and paperback volumes. In addition to its efficiencies and pricing advantages, this provided a convenient framework for branding; it was advantageous to have your work come out under the imprint of a well-regarded publisher or to have your article published in a prestigious journal in the company of the established intellectual elite. The photocopier first challenged this strategy by enabling ready reproduction of pages, articles, and chapters, and the recombination of these extracts into new, ad hoc collections such as course readers. With digital text, the logic of the database replaced that of the printed page. Publishers of online journals discovered that rigid subdivision of material into "issues" no longer made much sense. Large, searchable text databases like LexisNexis aggregated articles from numerous sources and supported retrieval by user-specified category, and the World Wide Web cross-connected huge structures of text with hyperlinks.

For a century and a half photographers, using the silver-based process, have captured complete images with definite spatial and temporal coordinates. The privileged role of the photographic image as reliable visual evidence has depended upon its wholeness and closure and the possibility of tracing it back to an unambiguous origin point. But digital cameras now decompose images into finite grids of pixels that may readily be sampled and recombined to produce seamless collages. Furthermore, digital images—both captured and synthetic—may be replicated indefinitely and endlessly circulated through the Internet. Distinctions among visual facts, falsehoods, and fictions are increasingly difficult to construct and sustain.[10]

From the perspective of architects, Napsterization is the culmination of a long process of mobilizing and recombining design information. It began with the use of portable templates to facilitate replication of standard shapes and profiles in buildings. With the emergence of print, architects began to publish descriptions of architectural elements and rules for their combination; great classical treatises, from Palladio's *Four Books* to Guadet's *Elements and Theory*, disseminated standardized languages of architectural form.[11] We are now entering an era in which descriptions of elements and rules are stored on servers as software objects, traded, varied, and recombined electronically, and eventually materialized by means of CAD/CAM production devices.[12] If Palladio were alive today, he would be looking to 3D digital modeling and peer-to-peer distribution technology, not to woodcuts of plans and elevations.

MODULARITY AND PORTABILITY

You can trade and recombine MP3 files, digital images, CAD models, and the like because they are modular; that is, they are standard units in consistent format. (If an MP3 player gets a file that isn't in this format, it won't open it.) More technically, the differences among MP3 files are hidden behind a layer of abstraction that allows them to be handled in a uniform way. Over time, computing environments have evolved increasingly sophisticated layers of abstraction, providing greater modularity, easier reuse, and enhanced capacity to recombine digital fragments into new structures.

In the 1960s, on the batch processing computers of the time, you could assemble Fortran programs by duplicating decks of cards encoding functions and subroutines, then shuffling them into desired sequences; rubber bands, sorting machines, duplicating machines, and cardboard boxes were important aids in this process. Similarly, data files were decks of cards terminated by punched end-of-file symbols. If you wanted to modify a line of code or a data record (to correct a typo, for example) you physically pulled a card and replaced it. But this was cumbersome, and furthermore, mutually incompatible compilers established strong "trade barriers" among computing subcultures centered on different machines.

By the 1970s, though, things had become much easier; at the terminals of timesharing mainframe systems, you could use simple filesharing systems, online function and subroutine libraries, and text editors to assemble and run programs (maybe in Lisp) electronically. Then local area networks, the Arpanet, and the Internet further facilitated sharing, reuse, and recombination of code—and provided fertile ground for development of the collaborative "hacker" culture. Meanwhile, programming languages and software engineering practices evolved to support creation of modular, portable, reusable code units rather than huge, monolithic software constructions of the past; in particular, languages like C++ enabled creation of highly modular software "objects," development of sharable object libraries, and use of convenient mechanisms, such as inheritance, to facilitate modification and combination of existing objects to produce new objects.

Eventually, as networked computing environments became standard, languages like Java combined the virtues of modularity with easy network distribution and ability to run immediately in just about any computing environment. At a technical level, there was now little to inhibit global free trade in software modules. Of course, though, you might still choose to inhibit such trade by deliberately introducing incompatibilities, or to erect security barriers against ill-behaved code you wouldn't want invading your machine.

Modularized, parameterized, mobilized software has enabled several competing production and distribution strategies. For example, the neo-Fordist, industrial strategy—as pursued by Microsoft and other large software firms—emphasizes organized division of labor, accumulation of corporate intellectual property, integration of as many functions as possible into a single, standard, product, closure and protection of that product (the source code is not available to users), branding, and market domination.

By contrast, the open source strategy—most vividly illustrated by the development of the Linux operating system—takes advantage of the creativity and enlightened self-interest of user communities to create shared intellectual capital.[13] In an open source production environment, source code is made freely available, users extend and modify it as appropriate to their particular needs and priorities, and contribute generally useful extensions and modifications to a common pool.

Most radical of all (and, so far, of least practical impact—though I would not bet against it in the long term) is the evolutionary strategy. In so-called "simulated evolution," software modules randomly mutate, they are evaluated by some specified fitness function, and according to their fitness values, they either survive in the common pool or are discarded.[14]

All of these strategies can work well under the right circumstances, and they can work in various combinations and flavors; the commonality is reliance on modular, malleable, mobile, electronic text as the enabling medium.

These network-enabled strategies of decentralized collaging, sampling, searching and exchanging, and open sourcing threaten established corporate approaches to creating, pricing, marketing, and protecting information products. Not surprisingly then, corporate interests have often resisted and even attempted to criminalize them.[15] Disney, Time-Warner, Microsoft, and Reed-Elsevier would have it that the value of digital information derives from easy distribution and wide consumer access to completed, packaged, impregnably encrypted and copyrighted intellectual products. But far greater societal value resides in its endless capacity for fluid adaptation, transformation, and recombination, within communities of interest, to produce new and unexpected outcomes. If publishers and record companies succeed in enforcing continuation of outdated, industrial-age norms and conventions into the network era, many of the advantages of free-flowing, readily recombinable digital information will be lost. The cultural cost will be enormous.

This applies not only to pure information products, but also to material products formed through the application of information. The binding of form to materials has been loosened. We are entering an era in which batches of material may readily inhabit different forms, and digitally specified forms may inhabit different materials.

In sum, we have to rethink Manufacturing 101 and reconsider strategies for controlling the means of production. We may still be a long way from the superhero nano ring or the future wittily extrapolated in Neal Stephenson's *The Diamond Age*—a world in which every household has "the feed," a nanopipeline that supplies atoms to matter compilers that produce whatever goods you need on demand—but conditions have fundamentally changed.[16] What now matters most is not having an inventory of valuable *things* in your possession, nor even the machinery needed to produce such an inventory, but *access* to the invisible, immaterial, digital specifications. It is all very Platonic, in a way; digitally encoded ideas exist somewhere in cyberspace, and physical artifacts are their imperfect, material realizations.

on online identity and concealment, see James Frenkel ed., *True Names and the Opening of the Cyberspace Frontier* [New York: Tor, 2001]).

41. In his highly skeptical *On the Internet* (New York: Routledge, 2001), p. 11, Hubert L. Dreyfus has related this point specifically to the hyperlinked network structure of the World Wide Web. He observes: "Clearly the user of a hyper-connected library would no longer be a modern subject with fixed identity who desires a more complete and reliable model of the world, but rather a postmodern, protean being ready to be opened up to ever new horizons. Such a being is not interested in *collecting* what is *significant* but in *connecting* to *as wide a web of information as possible.*"
42. Mark C. Taylor, *The Moment of Complexity: Emerging Network Culture* (Chicago: University of Chicago Press, 2002), p. 231. Somewhat similarly, Brian Massumi has suggested, in *Parables for the Virtual* (Durham: Duke University Press, 2002), p. 128: "The ex-human is now a node among nodes. Some nodes are still composed of organic body-matter, some are silicon-based, and others, like the ancestral robot arm, are alloy. The body-node sends, receives, and transduces in concert with every other node. The network is infinitely self-connectible, thus infinitely plastic. The shape and directions it takes are not centrally decided but emerge from the complex interplay of its operations."
43. In similar recognition of this point, there is now an emerging field of "cyborg anthropology"—the study of cultures in which the very definition of "man" is put into question by scientific and technological developments. See Joseph Dumit, Gary Lee Downey, and Sarah Williams, "Cyborg Anthropology," *Cultural Anthropology* 10, no. 2 (1995): 2–16; and Joseph Dumit and Gary Lee Downey, *Cyborgs and Citadels: Anthropological Interventions in Emerging Sciences and Technologies* (Santa Fe: School of American Research Press, 1997).

CHAPTER 4 DOWNSIZED DRY GOODS

1. Ryszard Kapuscinski, *The Shadow of the Sun* (New York: Knopf, 2001), pp. 229–30.
2. Decca sales literature made much of this in the postwar years:

> What did you do in the Great War—"Decca"?
> I was "Mirth-Maker-in-Chief to His Majesty's Forces"; my role being to give our Soldiers and our Sailors music wherever they should be. In that capacity I saw service on every Front—France, Belgium, Egypt, Palestine, Italy and the Dardenelles; Right in the Front Line and away back in Camps and Hospitals. All told, there were 100,000 "Deccas" on Active Service from Start to Finish of the War.

Quoted in *Jones Telecommunications and Multimedia Encyclopedia*, <www.digitalcentury.com> (accessed December 2002).

3. Since 1992, the Semiconductor Industry Association (SIA) has been monitoring the shrinkage of integrated circuit elements and publishing

predictions. The SIA's *International Technology Roadmap for Semiconductors 2002* <http://public.itrs.net/> (accessed March 2003) suggested that the limits were only a few years away.

4. They are also called microsystems and micromechatronic systems. For a snapshot of MEMS technology in the early 2000s, and some projections of future directions, see Committee on Implications of Emerging Micro- and Nanotechnologies, *Implications of Emerging Micro- and Nanotechnologies* (Washington, D.C.: National Academies Press, 2002).
5. Richard Feynman, "There's Plenty of Room at the Bottom," *Engineering and Science* 23 (February 1960): 22–36.
6. K. Eric Drexler, *Engines of Creation* (Garden City, N.Y.: Anchor, 1987). See also K. Eric Drexler, *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (New York: Wiley Interscience, 1992).
7. Committee for the Review of the National Nanotechnology Initiative, *Small Wonders, Endless Frontiers* (Washington, D.C.: National Academy Press, 2002).
8. For example, *Scientific American* provided a comprehensive, critical overview in a September 2001 special issue entitled "Nanotech: The Science of Small Gets Down to Business," vol. 285, no. 3.
9. Michael Crichton, *Prey* (New York: HarperCollins, 2002).
10. L. A. Bumm, J. J. Arnold, M. T. Cygan, T. D. Dunbar, T. P. Burgin, L. Jones II, D. L. Allara, J. M. Tour, and P. S. Weiss, "Are Single Molecular Wires Conducting?," *Science* 271 (22 March 1996): 1705–07.
11. Mark A. Kastner, "Artificial Atoms," *Physics Today* 46 (January 1993): 24–31. See also Richard Turton, *The Quantum Dot: A Journey into the Future of Microelectronics* (Oxford: Oxford University Press, 1995).
12. David Rotman, "The Nanotube Computer," *Technology Review* 105, no. 2 (March 2002): 37–45.
13. Harold Abelson, Don Allen, Daniel Coore, Chris Hanson, George Homsy, Thomas F. Knight, Radhika Nagpal, Erik Rauch, Gerald Jay Sussman, and Ron Weiss, "Amorphous Computing," *Communications of the ACM* 43, no. 5 (May 2000): 74–82.
14. Kimberly Hamad-Schifferli, John J. Schwartz, Aaron T. Santos, Shuguang Zhang, and Joseph M. Jacobson, "Remote Electronic Control of DNA Hybridization through Inductive Coupling to an Attached Metal Nanocrystal Antenna," *Nature* 415 (10 January 2002): 152–55.
15. Lawrence K. Altman, "Self-Contained Mechanical Heart Throbs for First Time in a Human," *New York Times*, 4 July 2001, pp. A1, A10.
16. Feynman, "There's Plenty of Room at the Bottom," pp. 22–36. Medical nanotechnology has since become an active research field; see Robert A. Freitas Jr., *Nanomedicine, Volume 1: Basic Capabilities* (Georgetown: Landes Bioscience, 1999), and <www.nanomedicine.com> (accessed December 2002).
17. Ray Kurzweil, "The Singularity: A Talk with Ray Kurzweil," *Edge 99* (25 March 2002), <www.edge.org/documents/archive/edge99.html> (accessed December 2002).

18. Their modern descendants, server farms, continue this tradition—but in modular rack rather than cabinet format.
19. Various subgenres emerged during the 1980s and 1990s—the tower, the cube, the pizza box, and so on; designers mostly focused on providing a stylish outer surface. In some models (such as the first Macintosh) the processor and monitor were integrated into a single box, while in others they became separate elements. As processor boxes shrank, and as thin plasma screens began to replace bulky CRTs, designers had greater freedom to shape these elements; Apple, in particular, took adventurous advantage of this possibility.
20. Japan led the way. J-Phone introduced Sha-mail (email with photographs) handsets in November 2000. They were soon followed by NTT DoCoMo and others. KDDI and Casio introduced a GPS-equipped model in May 2002. An increasing percentage of Japanese cellphones began to incorporate cameras, and there was speculation that sales of these hybrids would eventually outstrip those of conventional digital cameras.
21. In 2000/2001, the Kyocera Smartphone, the Samsung 1300, and the Handspring Treo were among the first successful products of this type.
22. For a detailed analysis of the "spaces on the human body where solid and flexible forms can rest," with particular reference to the design of wearable electronic devices, see Francine Gemperle, Chris Kasabach, John Stivoric, Malcolm Bauer, and Richard Martin, "Design for Wearability," *Proceedings of the Second International Symposium on Wearable Computers* (Los Alamitos, Calif.: IEEE Computer Society Press, 1998), pp. 116–22.
23. MIT news release, 14 March 2002, <http://web.mit.edu/newsoffice/nr/2002/isn.html> (accessed December 2002).
24. Catherine Dike, *Cane Curiosa: From Gun to Gadget* (Paris: Les Editions de l'Amateur, 1983).
25. Applied Digital Solutions began to market the implantable VeriChip, which held an identification number that could be read by a scanner, in 2002. University of Reading computer scientist Kevin Warwick gained considerable notoriety (if not research results) by having himself implanted with microelectronics in the early 2000s; see Kevin Warwick, *I, Cyborg* (London: Century, 2002).
26. MIT news release, ibid. The appropriation of images and scenarios from superhero comics was direct; the *Boston Globe* (28 August 2002, pp. A1, A6) gleefully reported that an image on the Institute for Soldier Nanotechnologies's Web site had been redrawn from the Radix comic book character Valerie Fiores—an armor-clad security officer with attitude.
27. For a snapshot of smart fabrics research and development efforts in the early 2000s, see Lori Valigra, "Fabricating the Future," *Christian Science Monitor*, 29 August 2002, <www.csmonitor.com> (accessed December 2002).
28. Duncan Graham-Rowe, "Remote Heartbeat Monitor Unveiled," NewScientist.com, 28 January 2002. (*Measurement Science and Technology*, vol. 13, p. 163.)

29. For a comprehensive introduction to the functions of clothing systems, see Susan M. Watkins, *Clothing: The Portable Environment*, 2d ed. (Ames: Iowa State University Press, 1995).

CHAPTER 5 SHEDDING ATOMS

1. As information economists are careful to point out, however, nonrival assets can certainly have market value. Electronically distributed stock prices, for example, can be reproduced at negligible cost. They have high value when they are up to the second and exclusive but rapidly decline in value with time and with wider distribution. For a detailed discussion of the differences between rival and nonrival assets, and the implications of these, see Lawrence Lessig, *The Future of Ideas: The Fate of the Commons in a Connected World* (New York: Random House, 2001).
2. Fred Lerner, *The Story of Libraries: From the Invention of Writing to the Computer Age* (New York: Continuum, 1998); Lionel Casson, *Libraries in the Ancient World* (New Haven: Yale University Press, 2001).
3. Henry Petroski, *The Book on the Bookshelf* (New York: Knopf, 1999).
4. Predictably, this eventually produced a bibliophile backlash. See Nicholson Baker, *Double Fold: Libraries and the Assault on Paper* (New York: Random House, 2001).
5. Vannevar Bush, "As We May Think," *Atlantic Monthly* 176, no. 1 (July 1945): 101–8.
6. <www.tlg.uci.edu> (accessed December 2002).
7. If you want to get picky about the physics, we can say that the corpus of classical literature is now embodied electromagnetically, and yes, electrons do have mass. But that is irrelevant at the level of everyday experience. My briefcase quickly gets weighed down if I load volumes of the Loeb Classical Library into it, but my laptop does not get any heavier if I download the *TLG* onto its hard drive.
8. <arXiv.org> (accessed December 2002). See also James Glanz, "The World of Science Becomes a Global Village," *New York Times*, 1 May 2001, D1–D2.
9. Paul Ginsparg, "Electronic Clones vs. the Global Research Archive," <arXiv.org/blurb/pg00bmc.html> (accessed December 2002). Ginsparg and the archive later moved to Cornell. For a brief history of arXiv, see Gary Stix, "Wired Superstrings," *Scientific American* 288, no. 5 (May 2003): 38–39.
10. <CogNet.mit.edu> (accessed December 2002). See also Marney Smyth, "The Community *Is* the Content," *Publishing Research Quarterly* 17, no. 1 (Spring 2001): 3–14.
11. <www.ArchNet.org> (accessed December 2002).
12. See, for example, MIT's DSpace, <web.mit.edu/dspace> (accessed December 2002).
13. National Research Council, *LC21: A Digital Strategy for the Library of Congress* (Washington, D.C.: National Academy Press, 2000), p. 3. On prospects

Qiblah indicates the direction of Mecca, and USA Masjid Locator finds nearby mosques. See Toby Lester, "Guiding Light," *Atlantic Unbound*, 13 January 1999, <www.theatlantic.com/unbound/citation/wc990113.htm> (accessed December 2002).

2. Location awareness is an aspect of context awareness—the ability to determine and make use of contextual information such as location, time and date, temperature, sound level, surrounding objects and people, and so on. Context-aware computing has been an active research field since the early 1990s. For an introduction and survey, see Guanling Chen and David Kotz, "A Survey of Context-Aware Mobile Computing Research," Dartmouth Computer Science Technical Report TR2000–381, 2000. On the interrelationships of mobility, wearability, and context-awareness, see Daniel P. Siewiorek, "New Frontiers in Application Design," *Communications of the ACM* 45, no. 12 (December 2002): 79–82.
3. Pioneering demonstrations of location-aware computing and communication were the Olivetti Research Active Badge system (Roy Want, Andy Hopper, Veronica Falcao, and Jonathan Gibbons, "The Active Badge Location System," *ACM Transactions on Information Systems* 10, no. 1 [January 1992]: 91–102) and the Xerox PARC PARCTAB system (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 [December 1995]: 28–43.) The seminal discussion of the uses of location-aware computing is Mark Weiser, "The Computer for the 21st Century," *Scientific American* 265, no. 3 (September 1991): 94–104.
4. The Swedish National Road Administration has pioneered the use of location-aware, customized warning systems on automobile dashboards. See Julie Claire Diop, "Sensing Speed Limits," *Technology Review* 105, no. 10 (December 2002/January 2003): 29.
5. This has, of course, raised considerable civil liberties concerns. See, for example, Stuart Millar and Paul Kelso, "Liberties Fear over Mobile Phone Details," *Guardian*, 27 October 2001; and Elizabeth Douglass, "Cell Phones Set to Track Call Locales," *Los Angeles Times*, 18 October 2001.
6. <http://www.uwb.org> (accessed December 2002).
7. For further details, see <http://gps.faa.gov> (accessed December 2002).
8. For even greater accuracy, quantum-enhanced procedures can potentially be used. See Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone, "Quantum-Enhanced Positioning and Clock Synchronization," *Nature* 412 (2001): 417–19.
9. In the mid-1990s, the U.S. Federal Communications Commission passed a plan to provide 911 operators with more precise cellphone call locations. Implementation turned out, however, to be a slow and difficult matter. In Switzerland, the FriendZone system pioneered location-based cellphone service in the early 2000s.

29. Wearable retinal scanning displays have, for example, been developed and marketed by Microvision. See <www.mvis.com> (accessed December 2002). On the development and importance of miniaturized see-through displays, see Erik Sherman, "Little Big Screen," *Technology Review* 104, no. 5 (June 2001): 64–69.
30. Ronald T. Azuma, Yohan Baillot, Reinhold Behringer, Steven K. Feiner, Simon Julier, and Blair MacIntyre, "Recent Advances in Augmented Reality," *IEEE Computer Graphics and Applications* 21, no. 6 (November/December 2001): 34–47, and Steven K. Feiner, "Augmented Reality: A New Way of Seeing," *Scientific American* 286, no. 4 (April 2002): 48–55.
31. Jean Baudrillard, *Simulations* (New York: Semiotext(e), 1983).
32. Cicero, *De oratore*, II, lxxxvi. Frances A. Yates tells the tale to introduce her classic study, *The Art of Memory* (Chicago: University of Chicago Press, 1966), pp. 1–2.
33. Yates, *Art of Memory*, p. 3.
34. Early examples of systems and proposals of this sort include GeoNotes, which advertises itself as "digital graffiti in public places," <http://geonotes.sics.se/> (accessed December 2002); WorldBoard (J. C. Spohrer, "Information in Places," *IBM Systems Journal* 38, no. 4 (1999), <www.research.ibm.com/journal/sj/384/spohrer.html> [accessed December 2002]); Graffiti, described as "a simple application which allows users to leave notes for people at various locations on the Cornell campus," <www.cs.cornell.edu/boom/2001sp/kubo/egraffiti.html> (accessed December 2002); CampusAware, <http://testing.hci.cornell.edu/context/campus_aware/> (accessed December 2002); Bits on Location, <www.datenamort.de> (accessed December 2002); MemoClip (Michael Beigl, "MemoClip: A Location Based Remembrance Appliance," <www.teco.edu/~michael/publication/memoclip.pdf> [accessed December 2002]); and 34 North 118 West, <http://34n118w.net/htmldir/descriptn.html> (accessed December 2002).

CHAPTER 8 FOOTLOOSE FABRICATION

1. Thoreau observed the ice harvest on Walden Pond and, characteristically, was not too happy about this intrusion of industry. The story of the New England ice industry is entertainingly told in Gavin Weightman, *The Frozen Water Trade: How Ice from New England Lakes Kept the World Cool* (London: HarperCollins, 2001).
2. Amy Harmon, "Music Industry in Global Fight on Web Copies," *New York Times*, 7 October 2002, pp. A1, A6; and Ariana Eunjung Cha, "File Swapper Eluding Pursuers," *Washington Post*, 21 December 2002, p. A1.
3. William J. Mitchell, "Roll Over Euclid: How Frank Gehry Designs and Builds," in J. Fiona Ragheb, ed., *Frank Gehry, Architect* (New York: Abrams, 2001), pp. 352–64.

4. For an early discussion of this development, from a publisher's viewpoint, see Jason Epstein, "Reading: The Digital Future," *New York Review of Books* 48, no. 11 (July 5, 2001): 46–48. On the future of books, publishers, booksellers, and libraries more generally, see Clifford Lynch, "The Battle to Define the Future of the Book in the Digital World," *First Monday* 6, no. 6 (June 2001), <www.firstmonday.org/issues/issue6_6/lynch/index.html> (accessed December 2002).
5. Brent A. Ridley, Babak Nivi, and Joseph M. Jacobson, "All-Inorganic Field Effect Transistors Fabricated by Printing," *Science* 286 (22 October 1999): 746–49; Stephen Mihm, "Print Your Next PC," *Technology Review* 103, no. 6 (November/December 2000): 66–70; and Joseph Jacobson, "The Desktop Fab," *Communications of the ACM* 44, no. 3 (March 2001): 41–42.
6. The possibility of designing your own shoes on the Web was pioneered by cmax.com. Other early customization sites offered computers (dell.com), automobiles (mini.com), kitchens (merillat.com), watches (sega.com), and homes (lindal.com).
7. Walter Benjamin, "The Work of Art in the Age of Mechanical Reproduction," in *Illuminations*, trans. Harry Zohn (New York: Schocken, 1969), pp. 217–51.
8. National Research Council, *The Digital Dilemma: Intellectual Property in the Information Age* (Washington, D.C.: National Academy Press, 2000).
9. This practice was anticipated, with earlier and less convenient technology, in the production of compilation tapes.
10. For a more detailed discussion of this point, see William J. Mitchell, *The Reconfigured Eye: Visual Truth in the Post-Photographic Era* (Cambridge: MIT Press, 1992).
11. For a discussion of the roles of print, see Mario Carpo, *Architecture in the Age of Printing* (Cambridge: MIT Press, 2001).
12. For some examples, see William J. Mitchell, "Dream Homes," *New Scientist* 174, no. 2347 (15 June, 2002): 38–42.
13. Eric Raymond, *The Cathedral and the Bazaar: Musings on Linux and Open Source by an Accidental Revolutionary* (Sebastopol, Calif.: O'Reilly, 1999). Pekka Himanen, *The Hacker Ethic and the Spirit of the Information Age* (New York: Random House, 2001).
14. For a convenient introduction, with practical examples from a wide variety of fields, see Peter J. Bentley and David W. Corne, *Creative Evolutionary Systems* (San Francisco: Morgan Kaufmann, 2002).
15. In the United States, the most egregious outcome of these efforts has been the Digital Millennium Copyright Act.
16. Neal Stephenson, *The Diamond Age* (New York: Bantam, 1995).