♦ The Next Fifty Years: Some Likely Impacts of Solid-State Technology

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What does technology hold in store for us in the second half-century of the transistor's existence? In an attempt to provide at least a partial answer to this question, this paper projects twelve present day trends into the coming decades. Fueled by exponential growth in the capabilities of electronic circuitry and the communications fabrics that interconnect them, the future promises a world of pervasive interconnection, customized products and services, much help with complexity, and exciting new appliances. Although this projection holds few individual surprises, the totality of what looms likely just one human generation from today amounts to little less than a fantasy world.

Introduction

"Be careful what you wish for," an old adage cautions, "you may get it." With unprecedented power in human hands, wishes in tomorrow's world will likely come true almost too easily. Anything we conceive of is likely to work perfectly, at least as measured by the specifications of its design. The real measure of success will come from how well it works with the needs of its users, other technology, and the human environment.

Predicting the future, an uncertain activity at best, can take many forms. In this case, I have taken a highly personal approach to extrapolating twelve present day trends into the future, devoting a page or so of conversational text to each topic, in part because the raw material for this work came largely from personal conversations. Because technology represents a fast-moving target, I have taken the midpoint of the next fifty years as the locus of these predictions. Without saying so explicitly, each section that follows presupposes just enough progress in accompanying software technology and systems architecture to keep things moving along. This balance stems from a benign conspiracy between users and their machines. On the one hand, humans quickly gobble up the fruits of each software advance by adding and exploiting new features. And on the other hand, designers of automated systems can usually depend on human backups at whatever point the current state of their art happens to run out of steam.

Moving to the predictions themselves, let's begin with the digital circuitry that underlies modern software and all the systems and services that flow from it.

1. For Silicon Technology, the Best Is Ahead

On average, we can look forward to a million-fold increase in the power of microelectronics. I see this boost in performance stemming from three roughly equal factors. First, a straightforward extrapolation of current photolithography should carry the industry to something like 0.05-μm design rules. Because such resolution amounts to about one-tenth of current levels, we can expect—from lithography alone—improvement in the range of two orders of magnitude in device density. Second, circuit speed will likely increase by a similar amount, owing to a combination of device speed and circuit design enhancements. As for the third factor, I can't imagine that something new won't surprise us in the coming decades.

This progress will not affect all types of circuits to exactly the same degree. For example, while advances in algorithms ought to boost processor performance

dramatically, progress in memory performance will likely track device technology much more closely. Silicon has outstripped its competitors for so long, and with such spectacular success, that suggesting alternative materials seems particularly risky. But potentially viable alternatives have already appeared—at least for specialized applications. Among these, so-called *plastic transistors* seem particularly worth mentioning. With the realization of reliable transistor performance in organic media, for example, we could see memory factories that produce printed plastic film by the acre.

Taken together, the sum of such advances should yield "low-end" computers more powerful than today's workstations for about the price of a postage stamp—and in postage stamp quantities, as described in **Panel 2**. Although they won't come equipped with keyboards or large displays at those prices, of course, these computers will recognize speech and connect to networked resources for help with their assigned tasks.

2. Very Affordable Bandwidth

*The per-bit cost of **global** data communications will drop by some three orders of magnitude.* Given the above-cited cost/performance boost in microelectronics, it seems reasonable to regard switching as "free," at least as compared to the relative cost of transmission in this new regime. At the same time, it doesn't seem unreasonable to expect a hundred-fold increase in fiber system bandwidths—from today's ten or so gigabits per second to a few thousand—with roughly constant system prices. If we take current system costs of backbone transmission as consuming about one-tenth of current infrastructure budgets, future operators ought to be able to afford a ten-fold increase in the number of transmission systems they buy with the money they will save on switching.

I see this as a case of technology moving to meet the needs of the marketplace—keeping prices affordable, while increasing bandwidth enough to enable high-quality multimedia services. At the present time, bulk Internet connectivity costs about one cent per megabyte. At one-thousandth of this amount, a full-time video connection between any two points on the globe would cost something like three hundred dollars per year—roughly the amount of money that an on-line household spends today. In other words, we should not be surprised to find explosive growth in "long distance" communications volume, accompanied by an equally dramatic diminution in its unit cost.

Panel 1. Abbreviations, Acronyms, and Terms

AMPS—Advanced Mobile Phone System
CMOS—complementary metal-oxide semiconductor
DRAM—dynamic random access memory
GPS—global positioning system
IC—integrated circuit
I/O—input/output
ISO—International Organization for Standardization
LAN—local area network
LEO—low Earth orbit
PDA—personal digital assistant

In terms of pure numbers, a thousand-fold change seems modest when compared to microelectronics or the bandwidth growth predictions made by cyberspace enthusiasts. (In the latter area, at least one projection presupposes an annual tripling of bandwidth over a twenty-five-year period, for example, or a cumulative increase of some three trillion times.) Looked at in terms of its potential impact, however, a "mere" thousand-fold increase in the number of bits shipped per dollar looms large. Imagine one billion on-line households, each able to command more long-distance data communication capacity than the entire Internet offered its users when the World Wide Web went global.

In addition to serving users with high-bandwidth "wired" connections, this fiber-based communications infrastructure will also support an equally dramatic growth in *wireless* systems. Unlike the "one size fits all" predictability of wider-bandwidth multi-wavelength fiber backbones, the infrastructure of our wireless future will support a great deal of diversity. Within this arena, users can look forward to an eclectic mix of system architectures that will vary widely in range, bandwidth, and coverage area.

Opportunities exist for infrared, acoustic, and long-wavelength radio links—as well as links in the microwave spectrum. Here, we can expect extensive use of flat panel array antennas. More space-efficient

Panel 2. Lucent Technologies' Advanced Video Processor

The AVP™ family of multimedia products was developed in 1992 as a three-chip solution that was predominantly hard-wired for the H.320 standard. This early product was called AVP-I. AVP-II, a more flexible solution, was introduced in 1994 and was sampled as either a two- or three-chip set, depending on the features needed for the application. AVP-II offered the system designer the opportunity to employ a lower-cost product. The latest product, AVP-III, was introduced in 1996 as a single-chip multimedia processor programmable to support multiple algorithms. Its design can be used either in a PC environment or embedded in other platforms. The programmability of AVP-III enables it to be selected for all of the popular or still emerging video compression standards, audio compression (including speech), and screen display graphics required by the multimedia market. When running at 67 MHz, the AVP-III has a processing power of 16 Gb/s. The control processor (see **Figure 1** below) runs the SPARC* instruction set and is supported by a direct memory access controller. AVP-III is fabricated in 0.35-μm three-level metal technology and contains 2.3 million transistors. The chip silicon area in 0.35-μm technology is 72 square millimeters, making it slightly less than 40% of the size of an Intel Pentium* Pro processor. During the next ten years, silicon technology will make the same functionality found in the AVP-III available in 1.4 square millimeters of silicon. Figure 1 compares the size of the AVP-III in 0.35-μm technology to its size in the 0.05-μm technology projected for the future.

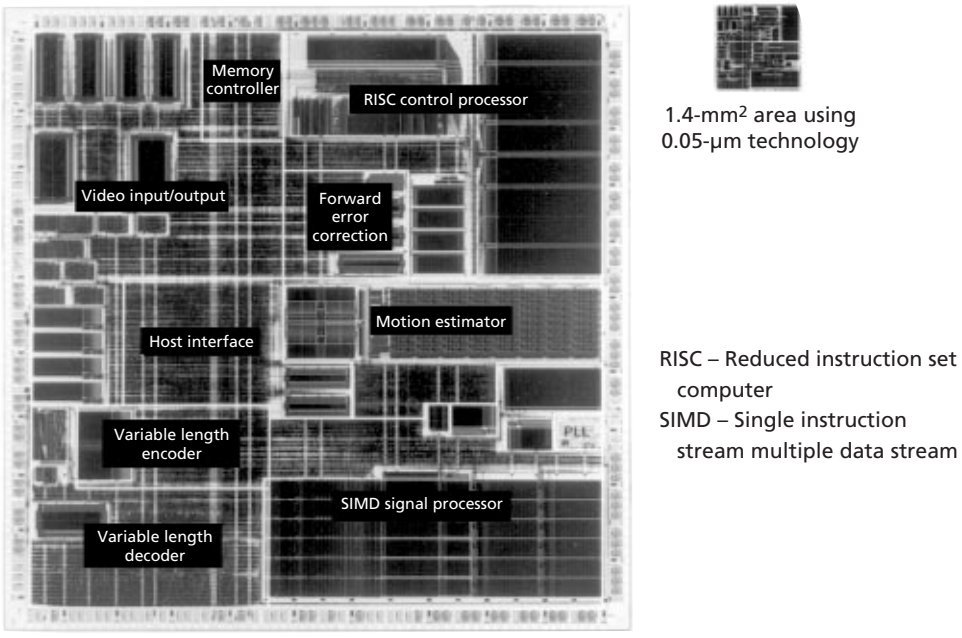

Figure 1.
Comparison of the physical size of today's AVP-III with its equivalent in the year 2007.

than today's dishes, these antennas can keep our environment from becoming cluttered with space-age paraphernalia. Easily blended into a wall or signboard, flat panels can finesse the physical limitations of conventional antennas. Moreover, each array's elements can be phased with respect to one another to produce desired beam shapes and directions, making the most efficient use of available power and bandwidths.

As in the case of microelectronics, communications technology should provide a dramatic boost to the systems and services that follow.

3. Interconnected Products

Interconnected products and services will become far more common—and will generally cost appreciably less—than their stand-alone equivalents. At first glance, such a state of affairs makes little sense. Why should *adding* capability lower the total cost? To see this emerging trend in action, let's look at a contemporary harbinger of things to come.

In 1996, a new device called the Palmpilot* grabbed 70% of the U.S. hand-held computer market, compared to 20% for Windows* CE hand-held PCs, and less than 10% shared among Psion,* Hewlett Packard products, and Apple's Newton.* In contrast to its remarkable success with users, however, the Palmpilot failed to excite interest among Silicon Valley's usually savvy venture capitalists. "Who needs another personal digital assistant?" they asked. Many offerings already contended in a market that attracted only a few buyers, after all. Despite their best efforts, the Palmpilot's designers couldn't raise enough money to bring their product to market and, instead, had to merge their operation into a larger company.

Why did so many knowledgeable financiers fail to recognize such a good opportunity? At first glance, the Palmpilot itself looks like nothing more than a stripped-down version of its predecessors. It has a small display, a Spartan touch screen for data inputs, limited features, and few of the back-ups that users have come to expect. For example, removing the pair of alkaline AA batteries that power the unit for more than a brief period causes a complete loss of all stored data.

But less is more—at least in this case. While virtually all hand-held computers include network connections, the Palmpilot's designers conceived of their personal digital assistant (PDA) as a networked offering from the outset—one that minimizes as much as possible the hand-held unit's share of any task. Linked to its owner's desktop computer via a plug-in connector, the Palmpilot relies on that desktop machine for much of what a Newton, for example, might normally do for itself. The result: a lighter, more compact, and less costly product—as well as a resounding marketplace success.

Looking to the future, we can expect electronic helpers of all kinds to execute increasingly complex tasks from minimal instruction. With microphones already cheaper than keypads, for instance, who will want to punch buttons (let alone remember which sequence corresponds to each particular task) rather than simply speak to the appliance in question? Customization will lead to software everywhere, along with multiple copies of each user's profile. And who will take the time to keep all this information current in stand-alone appliances? Clearly, users will opt for networked solutions.

From the perspective of consumers, the notion of getting a more functional product for less money may well seem counterintuitive at first. But they will get used to it soon enough, no doubt, and come to expect networked connection as a marketplace norm. And so will vendors. As we have seen from the PDA example above, producers can reduce the cost and complexity of their offerings by sharing capabilities that already exist elsewhere, rather than replicating them unnecessarily. Competitive pressure will likely drive rapid and far-reaching change in this arena—much as higher-quality products at lower prices from the Pacific Rim forced U.S. manufacturers to initiate radical process improvements.

In describing the impact of such process improvements, manufacturing theorists often refer to the *negative cost of quality*—that is, the notion that processes that perform perfectly actually cost less than sloppy ones. In much the same way, we can expect the *negative cost of networking* to become a similarly accepted business truism in the near future. The trend seems unstoppable. I venture to say that the same pair of drivers—customer demand and producer advantage—that have combined to make flawless performance a present-day marketplace norm will do much the same for network connections in the coming years (see **Panel 3**).

4. Real Home Networks

Future households will define themselves as much by their home networks as they now do by walls and fences. While today's home networks have barely emerged from their

infancy, early indicators already point to a major trend.

From a cost-of-service perspective, the pacing item will presently move from the so-called "last mile" to the "last meter." With a variety of technologies already poised to break today's "access bottleneck," some might well see nothing but smooth sailing ahead for on-line households. But life is rarely that simple. Again, we hear the echo of the adage "Be careful what you wish for." Whether or not consumers wished for all the communications offers that now confront them, options abound. So many exist, in fact, that few of us can name all the players without scorecards. Just consider the current list and then imagine how many more will likely enter this arena in the next few decades.

In addition to one or more "plain old telephone" circuits, upscale consumers can (or soon will) choose from the following service categories: digital subscriber line, cable, hybrid fiber-coax, fiber to the home, passive optical networks, cellular, fixed wireless, broadcast satellites, and low Earth orbit (LEO) satellites such as Iridium*—many from multiple vendors. On the appliance side, a number of new entrants now vie with familiar telephones and personal computers for consumer attention. They include, among others, network computers, smart telephones, PDAs, game machines, set-top boxes, Web TVs, and entertainment centers.

While a few brave—and technically astute—souls have managed to install commercial local area networks (LANs) in their home computing environments, this technology costs too much and does too little to fill the burgeoning needs of consumers and small businesses. In a typical office environment, for instance, managers of corporate management information systems count themselves lucky if they can support LAN nodes for as "little" as $3,000 to $4,000 per desktop per year. Moreover, LAN managers rarely offer anything approaching "plug and play" connections for even a restricted set of appliances and services, to say nothing of the "bestiary" cited above and all those that will emerge in the coming years.

Consider the plummeting cost of electronics and communication. Clearly, we can expect tomorrow's households to employ large numbers of computers and computer-driven appliances—most of them personalized to the specific requirements of their individual users. But that's just the beginning of the story. Taken together, these appliances and the customized network that interconnects them will mirror the human fabric that links the household's members together and will reflect their individuality as well. The technology needs of a telecommuting marketing executive who doubles as a soccer coach will, of course, differ significantly from those of a student council vice president with a mania for "Big Band" recordings, but differences make family life interesting.

Panel 3. Soft Radio

The exploding market for various wireless communication products has caused a flurry of activity in wireless standards and frequencies. In the early 1980s, only the Advanced Mobile Phone System (AMPS) protocol was available in the United States. Currently, there are seven or eight additional protocols in use or in the very early stages of introduction. During the next few years, the number of protocols will increase even further. From the perspective of the wireless customer, this creates a major problem when "roaming" between different service areas. For frequent travelers who carry their cell phone to different cities, this incompatibility is a great inconvenience. The ability of a cellular terminal to operate on more than the single wireless protocol for which it was designed would greatly reduce this problem and increase a cell phone's ease of use.

One promising solution to this problem is the "soft radio" now in development at Lucent Technologies. This cellular receiver will combine sophisticated processor technology with the ability to support silicon and software, enabling it to operate on a number of cellular protocols. The high frequency radio transmitter and receiver section of this particular cellular terminal will accommodate a range of frequencies, from less than 1 GHz to more than 2 GHz. Such a broad range is made possible by the use of enhanced modular silicon processing, being made available to the standard 0.35- and 0.25-μm complementary metal-oxide semiconductor (CMOS) technologies of the Lucent Microelectronics Group.

In bygone days, our forebears once recorded births, marriages, and similar milestones within the pages of a family bible. Although this is a rare practice today, something will surely take its place. Electronic family albums have already gained some popularity, and more applications seem likely to follow. Over time, electronics will capture more and more of a family's life story, from its art and entertainment to its work, finances, and the transactions of its daily life. The electronic home network thus will come to mirror its human counterpart.

What will it take to build and maintain tomorrow's home networks? This is a formidable technical problem, and the closer one gets to it, the harder it looks. Even so, someone will surely solve it. "Every engineer in Silicon Valley has a home network design on the back of the bench somewhere," a senior data-networking executive told me recently, explaining the apparent impossibility of meeting such a system's required performance in an affordable manner. His numbers looked persuasive, so it seems reasonable to assume that many will fail in the attempt. But those who finally succeed will likely find themselves at the heart of the next century's communications business.

As with most of today's networking technology, the cost of service and maintenance seems likely to dominate the economic picture. In this arena, therefore, tomorrow's local exchange carriers and their competitors will most probably base much of their business on providing service and support for these *tiny area networks* rather than their traditional central offices. For much of the past century, the "Telephone Company" not only provided reliable and easy-to-use telephone service at an affordable price, but also made the job look easy. Instantly on—and always available when needed—telephones get little respect from cyberspace enthusiasts, even as the latter struggle with their balky computer systems.

Today, of course, a wide range of choices and their accompanying complexity have made it much harder to provide the telephone's level of reliability and convenience, shifting at least some of the burden to consumers. Just think of how much tougher the job will become as services and appliances proliferate in the coming years. How complex will home systems become? I speculate that—much as marathons are usually decided at the limits of endurable pain—maintenance headaches will pace the march toward what appears possible from combinations of available components.

Among consumers, some dyed-in-the-wool do-it-yourselfers will likely balk at giving up control. They'll be free to do so. Most of us, however, will regard having a reliable source of help as a necessity, rather than an optional convenience. Whatever comforts a futuristically equipped home will offer its occupants, I wouldn't count on much in the way of simplicity.

In addition to its appeal as a source of service revenue, management of premises networks will bring other benefits to the companies that provide it. Imagine a group of communications companies, one of which determines the types of services the customer wants, hires other companies to supply whatever it can't provide economically, and draws up the bill. Nice work if you can get it, I'd say.

5. "The Net"

The Internet, telecommunications, and broadcast entertainment will blend into a single environment. Using a wide variety of networked appliances, a broad cross section of the world's people will make unself-conscious use of whatever combination of communication, transaction, and information/entertainment suits them best at any moment.

Present-day distinctions between modalities—such as television, chat rooms, 800 numbers, or Web pages—will mean little in this merged environment. A group of people will get together, discuss something of common interest, identify and obtain whatever information they need, and take action. An individual may seek advice, complete errands, learn, and check the sports scores. On-line or face to face, in business or social settings, truly top-notch technology ought to serve its users without burdening them with its internal workings.

But look how far we are from that ideal today. Imagine that a few friends want to arrange an evening out together. In today's world, such a task generally requires multiple phone calls and messages back and forth—comparing calendars, listing and examining

options, agreeing on a plan, and then making arrangements. Have I made it sound too complicated? Each pair-wise element of the task seems easy, but getting all the permutations aligned with one another usually takes a lot of work. Just think of the amount of time that even the best equipped of today's corporations devotes to the business analogues of such activities. Meeting after meeting crowds everyone's calendar. Who wouldn't welcome some help?

As much as most of us deplore meetings, we seem to need more and more of them in all aspects of modern life. Think of the friends cited above, or a physician consulting with colleagues about a difficult case, or would-be entrepreneurs hoping to put a new business together, or caregivers sharing strategies for dealing with a rare disability. The list seems endless.

Looking to the future, I picture such groups using electronic links to continually track the availability of would-be participants in order to bring them together as smoothly as possible in an on-line conference space. Within such spaces, the members of each group could engage in dialogue, examine relevant data, explore options, and take action. And all of this would be accomplished with no more effort than if they had been sitting together in a room with all the information in front of them. Does this sounds too good to be true? We've all watched well-rehearsed actors playing out such scenarios in futuristic advertising. Real people, of course, live in a much less ideal world.

A wide gap still separates such promises from current reality. While today's network technologies suffice for any single portion of this everyday activity, only a group of well-equipped computer enthusiasts could hope to accomplish the entire task in a coherent manner. And therein lies the value to businesses and the general public. Only the "Net" has a hope of supporting this blend of communication, transaction, and information/entertainment. Even then, integrating such services and making them available to a broad nontechnical community presents a daunting challenge. Given expected progress toward systems integration, however, today's stretch goals ought to become tomorrow's commonplace reality.

6. On-Line Shopping

The number and variety of targeted commercial and consumer offers will spur the pervasive use of software surrogates. This is simple self-defense. Who has enough spare time to attend to the flood of unsolicited information that rains down on us?

And matters seem likely to get worse. Tough times lie ahead for vendors who remain content to offer any but unique products on fixed terms. Just look at today's buzzwords: customization, lot size of one, one-to-one marketing, bundled offers, and the like. With every vendor in sight scurrying to customize offers, even seemingly mundane activities such as selecting a kitchen appliance may well take on epic proportions. Want a new microwave oven? How about one that starts to warm up your dinner whenever you've cleared the last traffic jam on the way home? Or one that measures the fat content of everything it cooks and sends the tally to your diet program? Pick the features you want, and they're yours. Decisions, decisions, decisions.

Today, most of us frequently trade cost for convenience when we go shopping—like buying a somewhat higher-priced tube of toothpaste in the supermarket to avoid making a special trip to the drugstore. But "special trips" hold little meaning for on-line shoppers. At worst, price comparisons require no more than a few mouse clicks and some waiting for the screens to fill up. Furthermore, a growing number of service providers will happily make such "trips" for shoppers (in return for a bit of advertising) and provide an ordered list of vendors who offer the item in question, along with their prices. Because few vendors would relish competing on price alone, the incentives to create customized offers seem self-evident. Alongside these pressures, we note the plummeting cost of transactions, so technology works to make customized offers a matter of convenience, as well as necessity.

Price competition—and vendors' efforts to obscure it—predates the Internet by a wide margin. Numerous companies proclaim their call minutes, seat miles, or television sets to be the "best buy." And why not? Under various circumstances, each item can probably lay claim to that particular distinction. Major appliance retailers, for instance, frequently arrange to have manu-

facturers make minor modifications to a particular item and then confidently offer a cash reward to anyone able to buy that same model for less money elsewhere.

Pity the poor comparison shopper. On the Internet, at least, electronic agents can't get arrested for trespassing—the fate of more than one human who browsed stores with notebook and camera and didn't leave quickly enough to suit an irate store manager. But electronic agents don't have it all that easy either. Internet retailers can pose as potential buyers, for example, to see how various on-line comparison shoppers rate their offers. If a rating falls below expectations, the retailer can lower the price and raise fees for shipping and handling, bundle one item with another, offer extras, and then try again. And so it goes.

As complexity mounts, I speculate that the adversarial nature of comparison shopping will limit the utility of public agents in this arena. Moreover, individual buyers may well resort to the "request for proposal" (with the help of their personal agents) to put themselves in a better negotiating position with would-be suppliers.

Perhaps we might best relate such an environment to present-day experience by considering the complexity surrounding the deals that most of the world's airlines strike when ordering major additions to their jet fleets. The more you commit to buy, the lower the price, or the better the financing terms. Trade-ins, maintenance contracts, and rebates on purchases of other products also become part of the deal. The list goes on and on. And why not? Aircraft manufacturers know their customers' individual needs and circumstances in exquisite detail. Furthermore, the size of each order can justify any amount of sales and marketing effort. While these are modern people buying and selling modern goods, future transactions may well bear a much closer resemblance to an oriental bazaar than to the check-out line at Wal-Mart.

With few consumers likely to get less busy in the coming years, who will have time to participate in any such bazaar-like environment in the course of everyday life? A personal purchasing system, naturally. Enter the customized shopping program—or family of programs—ready to sort through complex offers on behalf of its employer. Such software-based surrogates will select the packages that appear to match their owners' needs and preferences most closely, making purchases and/or recommendations according to preset limits. Because marketing programs will likely create most of these customized offers, we face the prospect of a world in which machines will engage one another in a futuristic version of one-on-one marketing. In an increasingly noisy world, we can only hope that the work of these stand-ins will afford humans a few extra quiet moments.

7. Living in a Glass Village

Except for those willing to go to much trouble and expense, large portions of what we now regard as privacy will diminish greatly, or even disappear altogether. In place of today's urban anonymity, the average citizen will most likely encounter a level of name and face recognition heretofore experienced only by celebrities and the inhabitants of small villages. Technology—in the form of low-cost, high-quality and ultra-compact digital cameras—will drive this change. Over time, these digital cameras will find multiple uses, starting with security, transaction verification, and legal liability issues, and moving on to applications in targeted marketing.

While many people seem to see government snooping as the greatest threat to individual privacy, I see less sinister—but far more powerful—forces at work: the simple self-interests of countless businesses large and small, and those of the people who work for them.

Imagine how much someone working in a late-night gas station or convenience store, faced with the specters of shoplifting, worthless checks, and credit cards—let alone the possibility of a hold-up—has come to appreciate the deterrent effect of a video camera. Moreover, similar needs exist in a wide range of other environments. In the professional lines of work, teachers, physicians—indeed anyone who might get sued for alleged misbehavior in the course of his or her work—might also value a videotape record of an altercation with a student, a medical treatment, or just someone tripping on the office carpet.

On a more positive note, many merchants and other business people will likely welcome an electronic memory aid, one that could help them greet customers by name. Beset by competition, vendors can

hardly be blamed for wishing to personalize their customer relationships once they discover that their computers can recognize human faces. As a result, I think that we can expect a kind of "caller ID" for personal encounters. In the next few years, machines will surely learn how to extract speech samples and facial features, as well as to infer other parameters—such as height, body build, and gender—that could help identify the customer in question on subsequent visits.

If you find this a wonderful memory aid for remembering names and faces, how about a miniature unit, fitted with an unobtrusive earphone prompter? I can see the ads now. "No more embarrassing encounters. Improve your social life. Start a new career as a maitre d'." A bit scary though, isn't it?

No matter how deep and well-argued privacy concerns become, however, I cannot imagine a combination of actions or circumstances that could block the deployment of such technology for any significant amount of time. What can anyone do, after all? It would only take one computer whiz anxious for an improved social life and willing to post software on the Web. Like it or not, big city anonymity may well prove a momentary detour in the social history of our species. In its place, most of us will find ourselves living in small towns with potentially nosy neighbors. Hiding in such a "glass village" will take a lot of work.

8. My Very Own PC

Truly personal computers will become as much a part of twenty-first century clothing as today's wristwatches. Given the plummeting cost, shrinking size, and increasing unit performance of electronic circuitry, we can take the existence of pocket-sized (and smaller) computers for granted. But what about displays, power sources, and I/Os?

Imagine an ultra-tiny LAN, one that combines low-power radio with wires woven into the wearer's clothing. A wallet-sized primary unit holds the processor, main memory, and primary battery, together with local and wide area communications capabilities. An earphone and one or more microphones (which double as jewelry) connect to the primary unit via low-power radio links—providing prompts and commands to and from the user, as well as acting as a collector of audio information from the surrounding environment. A specially fitted pair of eyeglasses completes the picture. A pair of tiny video cameras, mounted at the upper outside edge of the eyeglass' lenses, gives the system a stereoscopic image of the wearer's field of view. In addition, even tinier lasers mounted on its temples provide a heads-up display—much like what we now see in the cockpit of a jet aircraft or even the windshields of some upscale cars.

Through network connection and built-in navigation aids, the wearable unit locates and arranges for access to ancillary devices—such as a printer or automatic teller machine—in the user's vicinity. In doing so, this personal computer blurs today's distinctions between a PC, telephone, PDA, and even a smart card, while adding a host of new functions.

9. The End of Lines—GPS Becomes Indispensable

Networked alternatives to congestion rationing will extend the just-in-time concept to consumer services. The mechanism that economists term *congestion rationing* acts to limit access when demand exceeds the available resources in question—such as attention at an airline counter, access to a computer help desk, or transportation at rush hours. In today's world, time and energy wasted in waiting seem an inescapable fact of life for all but the super-rich. Fortunately, technology appears poised to improve that situation in the coming years. Bits, after all, seem better suited to queuing patiently than humans do.

Imagine, for example, a transportation system capable of luring commuters away from driving their cars to work. In this scenario, a combination of global positioning system (GPS) technology, mobile communications, and networked computing would offer dispatchers and potential riders complete and instantaneous access to vehicle status and location information, as well as to traffic conditions. Such a system could encompass a wide range of services—from precisely timed door-to-door taxis, to guesswork-free trips on public buses.

In the former case, a software agent might "hail" the nearest available cab and determine its precise arrival time, for example. In the latter, the bus company's home pages might feature street maps, with

moving blips of light representing the active vehicles in its fleet—and with other types of information, such as the number of empty seats and the anticipated departure times from stops along each route, all available at the click of a mouse.

In addition, I foresee multipassenger vans offering door-to-door service. With schedules negotiated on the fly, passengers (or their agents) might arrange for en-route rendezvous with friends or colleagues. And customization needn't stop there. Multiple levels of service seem likely, from nonstop travel for time-pressed executives, to roundabout routes for the most budget conscious.

Is this a glimpse into the future, or merely a technologically driven speculation? Drivers, conventional wisdom tells us, love their cars too much for them to ever give up their steering wheels for something else. But that love affair seems less robust as traffic gets worse and worse. According to U.S. government data, for example, the number of miles driven annually has increased 30% in the last twenty years, with only a 1% increase in highway mileage. Tragically, according to that same report, more than half of all U.S. highway deaths stem from lost tempers by one or more of the drivers involved. This is a stormy love affair at best, and one that exacts an increasingly high price.

A growing number of present-day trucking companies already use GPS-based dispatching systems. And what holds for today's parcels seems poised to apply to tomorrow's commuters. The city of Paris, for example, recently introduced GPS technology in its public bus system, as have taxi operators in Amsterdam, Berlin, and Singapore. As of now, only dispatchers get to track the vehicles in these fleets, but public access to this kind of information—and all conveniences that will flow from it—seems only a matter of time.

Though important in itself, such a development represents just one early example of a larger trend. The navigation systems that we now see in commercial vehicles and luxury automobiles will presently find their way into multipurpose pocket-sized devices. Over time, applications will touch upon most of our everyday errands. Do you dislike having to wait in line for your early-morning "tall nonfat latté?" You can look forward to having it waiting for you—piping hot and already paid for—just seconds before you step inside the coffee shop.

A wide range of other applications lies between this rather frivolous example and the restructure of our entire transportation system. But all share one important element: addressing wasted time as a quality-of-service issue.

As with any institution, progress in a particular area will depend on its level of competition. But even those who are captive and waiting their turn at an understaffed help desk can look forward to less time spent listening to a series of recorded announcements. Even today, leading-edge call centers offer the option of leaving your number for an automatically scheduled return call. Much as process improvements have boosted the quality of manufactured goods, just-in-time service ought to set a new quality standard for consumer services.

10. Corporations Focusing on What They Do Best

Specialization, rather than vertical integration, will dominate the next century's communications and information services businesses. This trend stems from three drivers: the pace of innovation, growing complexity, and market demand for interoperability.

In earlier times, industrial era enterprises—tuned through long experience to their own specific needs—tried as much as possible to organize themselves around dedicated sources of supply, so as to assure themselves of optimal components. At one time, therefore, the world's premier telephone company did everything from making house calls to mining sand from a particular South American beach for the quartz crystals in its electronic oscillators.

But this scenario no longer holds true. Thanks to end-to-end computer-based process control, the marketplace abounds with products and services precisely tuned to customer needs. Moreover, with new and better products and services appearing with breathtaking speed, proprietary offers tend to age rather quickly.

As complexity grows, acquiring and sustaining all the skill sets needed for across-the-board excellence will become ever more difficult, as well as less rewarding. Instead, competition will force companies in all

fields of endeavor to limit their activities to those things they do best—and to source the rest from leaders in their respective arenas.

Finally, to meet the demand for interoperation, successful competition for markets will hinge upon successful competition for the most desirable partners. Toward that end, each enterprise will have to work hard to strengthen its own appeal to potential allies.

In telecommunications, for instance, a single "network" may well involve almost as many vendors as there are layers in an ISO protocol stack. In this connection, I speculate that most traditional "telephone" companies will find it difficult enough to extend their experience with physical and link layer services to the network layer, say, and will likely leave application layer services to specialized providers. Conversely, online service providers, and the like, will increasingly leave ownership and management of facilities in the hands of others. Instead, they ought to focus their own efforts on enriching the experience they provide to their customers, through services such as a truly helpful "personal" help desk, for example.

How far will this trend take future businesses? Some foresee an era of so-called *virtual corporations*—one in which each enterprise forms and re-forms itself from a pool of self-employed individuals, hired to meet the needs of the moment. But winning teams don't spring up overnight. Instead, shared learning, complementary skills, mutual trust, and practice in working together combine to create entities greater than the sum of their parts. Economies of skill—rather than economies of scale—seem likely to dictate the size of tomorrow's most rewarding institutions.

11. Winning the Struggle Against Disease

Humankind's ability to map, simulate, and modify biological molecules will shift the frontier of medical research from one of dealing with disease to coping with issues of longevity.

How big is an atom? When a group of young students asked me this question, my rejoinder was "How many grains of salt would it take to fill a salt shaker the size of New York City's Empire State Building?" They replied, "A really, really big number." "Well," I told them, "a single grain of salt holds an even bigger number of atoms. Imagine measuring anything that small."

Today, electronic technology enables biologists to make atom-sized measurements by using:

- Sensitive probes with submicroscopic resolution,
- Data processing to extract and process the complex spatial relationships that characterize biological molecules, and
- Computer simulation of the processes that govern such structures and organisms.

While further progress depends on the continuing efforts of dedicated scientists and physicians—just as Moore's Law depends on a continuing stream of inventions in our own industry—the steady passage of milestones suggests a secular trend for some years to come.

In particular, while mapping the human genome has taken years and billions of dollars to accomplish, we can expect similar efforts on other living systems to take no more than a tiny fraction of that effort. In addition to the fact that tools grow more powerful almost daily, other living systems are simpler to map and share many of our (now known) characteristics. As a result, we may well enter an era in which biology will undertake the reverse engineering of pathogens with much the same zeal and success that marks similar efforts in today's electronics business.

While people will still *get* sick in the future, it will likely become much harder to *stay* sick—and even less likely to die as the result of any such malady. Furthermore, as progress in electronic and mechanical technologies keeps pace with medical understanding, so will our ability to replace worn out or defective components in the chain that supports human life—from prosthetics to refurbished chromosomes.

While many others have made the same point, and with far more authority, I nonetheless feel it necessary to include this important consequence of technological progress. The present state of molecular biology would have been inconceivable without the invention of the transistor and all that has flowed from it—just as advances in the coming years will depend in significant measure on the emergence of far more powerful electronic tools.

As time goes on, I think that we can expect biology to begin to repay the technology debt it owes to

the physical and information sciences, and to do so handsomely. At the very least, biology shows us how much further truly "high-tech" tools might take us in areas as diverse as information storage, pattern recognition, decision theory, and microchemistry. Compare dynamic random access memories (DRAMs) to DNA, for example, as we do in **Panel 4**. Each strand of DNA comes equipped with its own repair engines. Scurrying up and down each double helix, these engines sniff out and repair damaged molecules one by one. Clearly, much room for progress will remain long after Moore's Law has run its course. And in that progress, biology can serve as a benchmark as well as a guide.

12. The Past Record of Futurists

Predictions about the future—this paper included—will be shown to have underestimated the pace of technology and overestimated its impact on human society. Examples of this perennial habit abound. Just think of the "life in the future" exhibits you have seen at your favorite theme park or world's fair. How quickly reality passes them by.

Speaking personally, I recall a mid-sixties compendium of predictions made by America's leading technologists, who were asked to peer twenty-five years into the future. None of their technology predictions took as long as the end of that decade to come to fruition. On the other hand, they envisioned that same technology supporting twenty-hour work weeks, widespread telecommuting, and almost complete elimination of classroom instruction. With all that (hand-wired) technology, they reasoned, whatever work anyone needed to do could be accomplished anywhere.

What would those same engineers say to today's technology, and the fact that the majority of Silicon Valley's venture capitalists choose to cluster along the same short stretch of road—or that almost all of the world's high-quality ceramics come from companies located within a short drive of Bologna, Italy? In both cases, community members evidently benefit from physical proximity.

What benefits does such proximity offer? Among other things, neighbors provide one another with day-to-day recourse. It's not just a matter of "Sue me if you don't like it." You have to face your neighbors if you act badly. In Silicon Valley terms, your physical presence shows you to be more committed, willing to show the community who you are through your day-to-day behavior. In the case of a long-established community such as Bologna's, family relationships come into play. Your children may well marry someone from that community, so you'd better not misbehave. In an atmosphere of trust, people feel freer to share information as well as infrastructure, so learning and cooperation take place.

Both of these examples illustrate the limitations of so-called *virtual communities*. "On the Internet, no one knows you're a dog," as cartoonist P. Steiner so aptly depicted in the *New Yorker*. This is acceptable behavior for a chat room, I suppose, but cyberspace seems a less reliable source of trustworthy neighbors than do traditional human institutions. In this connection, citizens of (real) communities have long organized their internal and external interactions through the mechanism of government. While cyberspace enthusiasts use words like "sovereignty" and "community," this medium can offer only minimal recourse to its users. In the absence of outside help, the cyberspace equivalent of capital punishment amounts to nothing more than forcing miscreants to change their logins.

This "outside help" underlies continuing roles for government in areas such as protection against fraud, fair trade, the validation and protection of intellectual property, and—most important—sustaining a continuing basis for those everyday amenities that the "Net" is supposed to improve. Just look, for example, at the dramatic differences in economic progress that have accompanied the opening of various national markets. Borders matter a lot in a global economy. Just ask anyone who makes investment decisions.

As I hope these examples illustrate, even the most powerful of our technologies leaves more intact than we might imagine. Moreover, we humans often use technology to maintain the status quo in the face of unwelcome pressures for change, such as in past oil crises. For better or worse, deep-water drilling, improved vehicle efficiency, and the like allow motorists to carry on as before.

As the number and power of our tools grow, so do

Panel 4. The Vanishingly Small

In the last thirty years, the typical feature size of an integrated circuit (IC) has shrunk dramatically, as shown in **Figure 2**. The success of the experimental arrangement of Shockley, Brattain, and Bardeen depended on dimensions of about 75 μm. Today's typical IC contains features of about 0.30 μm, almost 250 times smaller than the dimensions of the original Bell Labs apparatus. Researchers now believe that the ultimate dimensional limit of ICs will be about 0.05 μm, down another factor of 6 from where ICs are today. Further breakthroughs will occur, researchers believe, to allow circuits to be built with dimensions beyond the presently perceived physical limits.

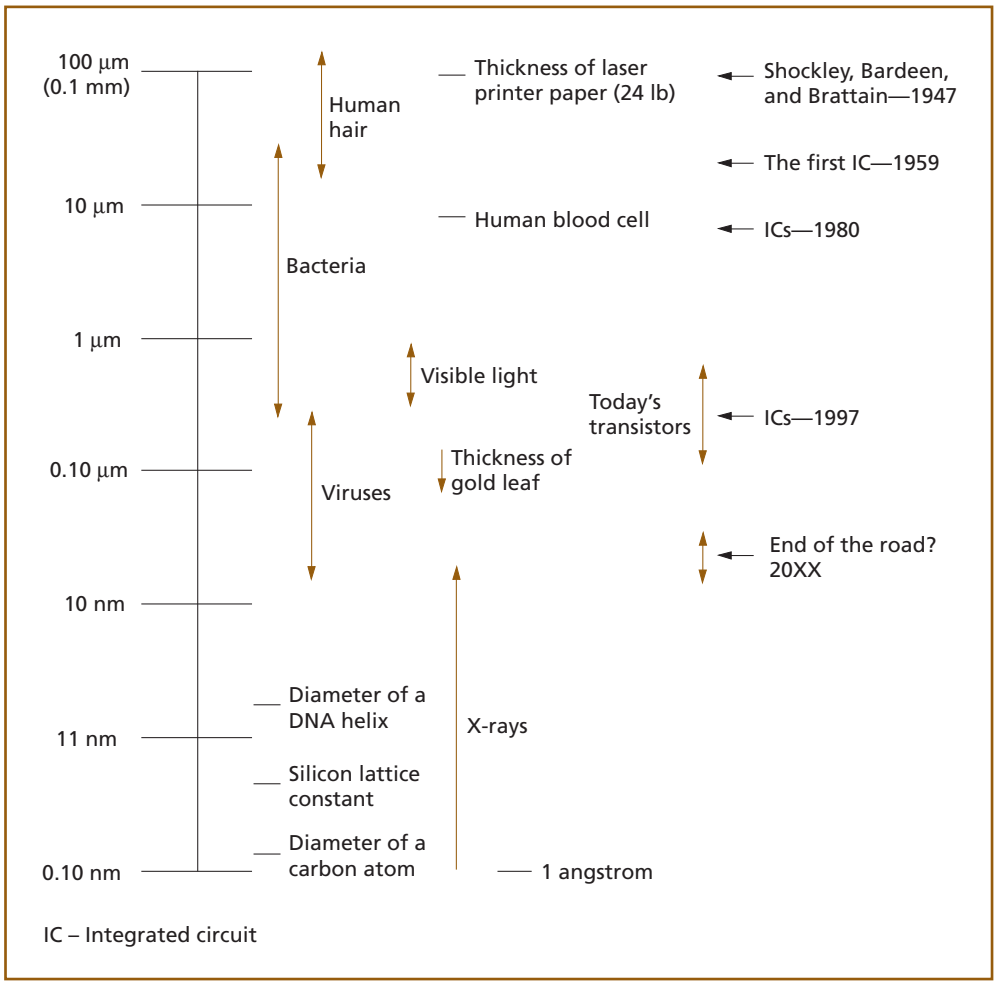

Figure 2.
The vanishingly small IC.

our options. Computers, their networks, and all they connect to can help humans reach almost any goal—but the choice of goals belongs to humans alone. Tools supply the power; humanity must supply the direction. Technology, therefore, will likely make us what we already are—only more so.

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