Networked Computing in the 1990s

Computers began as cumbersome machines served by a technical elite and evolved into desktop tools that obeyed the individual. The next generation will collaborate actively with the user

by Lawrence G. Tesler

In the 1970 film *Colossus: The Forbin Project,* a computer climbs to world domination from the caverns of a hollowed-out mountain, where cabinets decked with flashing lights and spinning tape drives are tended by an army of white-coated programmers.

The stereotype changed between 1977 and 1982, when personal computers entered homes and offices. The new reality was reflected in movies soon afterward: the 1987 film *Wall Street,* for example, portrayed a machine that had shrunk to desktop size, its lights and tapes replaced by a cathode-ray tube, a keyboard and a mouse (that is, a roller that manipulates a pointer on the screen). The priesthood of programmers had vanished, to be replaced by a single user—in this case an investment banker—for whom the computer was a tool, not a calling.

Movies of the 1990s will portray the machines as inconspicuous devices—more like watches than clocks. They will have thin, flat screens, microphones or styli instead of keyboards, and wireless transmitters rather than cable-bound modems. Moreover, their relation to the user will change from that of an isolated productivity tool to that of an active collaborator in the acquisition, use and creation of information, as well as a facilitator of human interaction. Of course, these predictions and others I shall presently make reflect my personal views. Most, however, are widely accepted in the computing profession.

It is generally believed, for example, that the computer will come to play a much more active role by collaborating with the user. The collaborating agent may not even be confined to a particular device. It might move, for example, from palmtop to mainframe data base to desktop. The user, moving from office to car to meetings, might give an electronic agent the following tasks:

• On what date in February did I record a phone conversation with Sam?

• Make me an appointment at a tire shop that is on my way home and is open after 6 P.M.

• Distribute this draft to the rest of the group and let me know when they've read it.

• Whenever a paper is published on fullerene molecules, order a copy for my library.

Programmers will make agents seem intelligent by endowing them with certain reasoning capacities. Agents will consult data bases, and when stumped they will ask the user for guidance. They will be rather like a human assistant, except that they will lack intu-

The Four Paradigms of Computing

	BATCH	TIME-SHARING	DESKTOP	NETWORK
DECADE	1960s	1970s	1980s	1990s
TECHNOLOGY	MEDIUM-SCALE INTEGRATION	LARGE-SCALE INTEGRATION	VERY LARGE SCALE	ULTRA LARGE SCALE
LOCATION	COMPUTER ROOM	TERMINAL ROOM	DESKTOP	MOBILE
USERS	EXPERTS	SPECIALISTS	INDIVIDUALS	GROUPS
USER STATUS	SUBSERVIENCE	DEPENDENCE	INDEPENDENCE	FREEDOM
DATA	ALPHA-NUMERIC	TEXT, VECTOR	FONTS, GRAPHS	SCRIPT, VOICE
OBJECTIVE	CALCULATE	ACCESS	PRESENT	COMMUNICATE
USER ACTIVITY	PUNCH & TRY (SUBMIT)	REMEMBER & TYPE (INTERACT)	SEE & POINT (DRIVE)	ASK & TELL (DELEGATE)
OPERATION	PROCESS	EDIT	LAYOUT	ORCHESTRATE
INTERCONNECT	PERIPHERALS	TERMINALS	DESKTOPS	PALMTOPS
APPLICATIONS	CUSTOM	STANDARD	GENERIC	COMPONENTS
LANGUAGES	COBOL, FORTRAN	PL/I, BASIC	PASCAL, C	OBJECT ORIENTED

ition and the ability to improvise. They will, however, be able to identify recurrent patterns in the user's work, inspect incoming messages and take note of deadlines. Armed with such information, agents will often anticipate needs before the user has expressed them or has even become aware of them. A mobile computer might catch up with its user at breakfast time:

• You asked me when you last recorded a phone conversation with Sam. It was on February 27. Shall I play the recording?

• You scribbled a note last week that your tires were low. I could get you an appointment for tonight.

• Laszlo has discarded the last four drafts you sent him without reading any of them.

• You have requested papers on fullerene research. Shall I order papers on other organic microclusters as well?

Although the commands and responses are represented here as typed English sentences, other forms are possible. They might be handwritten or spoken, more or less grammatical and explicit, in other human languages or perhaps in a more rigid computer language (such as SQL, a language designed for querying data bases). They might be specified by checking off options and filling in blanks on a form or by providing terse answers to a series of questions posed by the agent.

The changes in the computer's role—from cloistered oracle to personal implement to active assistant—have come in distinct waves that can be likened to paradigm shifts, the term by which Thomas S. Kuhn, a philosopher at the Massachusetts Institute of Technology, describes revolutions in scientific thought. Computing paradigms are made possible by steady improvements in a variety of technologies, together with a maturation of the market. They seem to happen at intervals of about a decade.

The original computer paradigm was invented in the late 1940s, when the programmable calculator was designed as an engineering tool; it became commercially practical in the 1950s. The first shift came in the 1960s, when the computer was adopted as a data-processing engine by corporations. The second came in the 1970s, when the computer's services were shared among many subscribers. The third shift, in the 1980s, transformed the computer into a desktop productivity tool for individ-

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THE IBM 360, circa 1964, processed sequential batches.


THE DECsystem-10, 1975, provided time-sharing.


APPLE COMPUTER'S Macintosh IIci personal computer.


APPLE'S projected software agent: roamer of networks.

uals. The fourth is now under way. Its harbingers are the increasingly networked laptop devices and electronic pocket calendars—mobile machines I call pericomputers. Pericomputers are valuable both for the limited functions they can perform in isolation and for the access they afford to an electronically embodied world of information.

Each shift has fundamentally altered the way people perceive computers. In the 1960s, for example, computing power was dear, and matters had to be arranged at the machine's convenience, as it were. Data had to be processed in huge batches for the technology to pay its way. Only very large organizations could generate such batches. Companies would, for example, run a payroll program to process the week's time cards, then immediately load another "job"—a program with its accompanying data—into the computer. Jobs were coded on punched cards or magnetic tape, and results were delivered as "listings" printed on fanfold, perforated paper. The computer would stop at any error it encountered, in program or data, and return the faulty job to the customer for corrections, a maddening process when reiterated over many hours or even days.

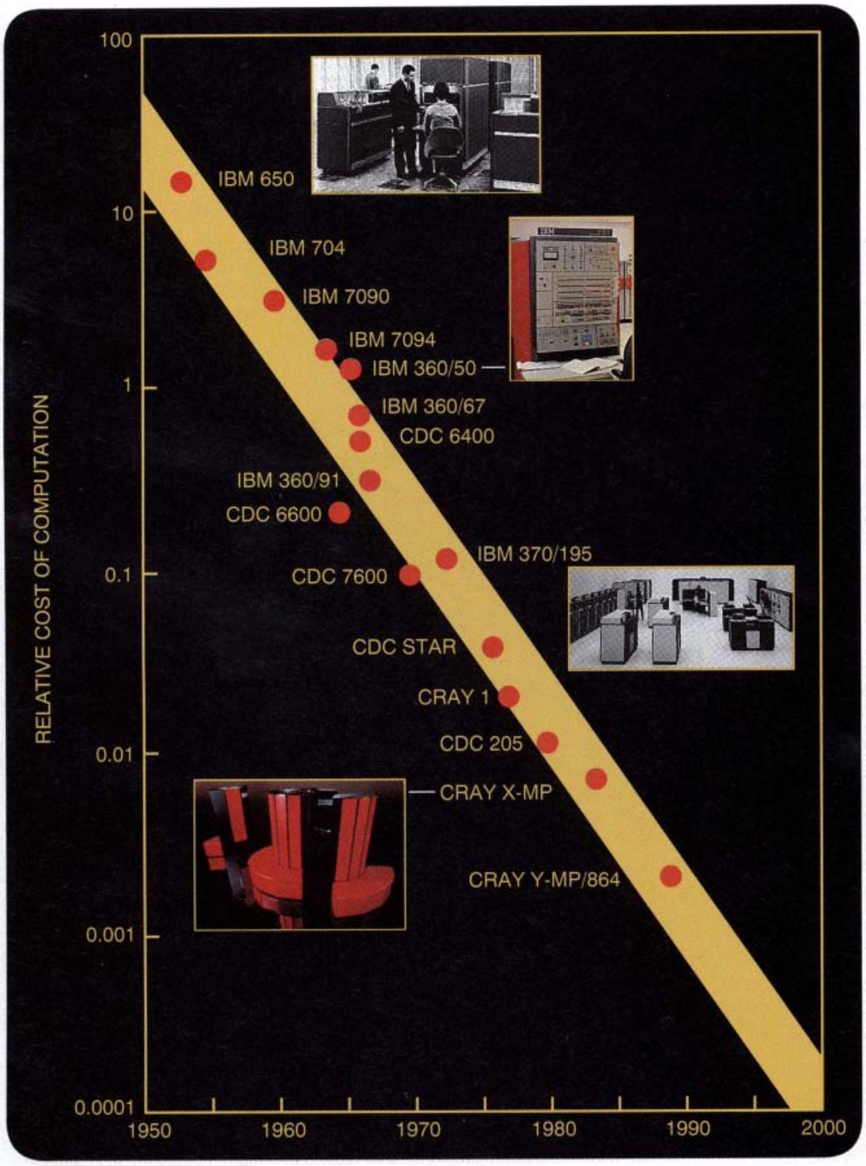
In the 1970s time-sharing made data processing more affordable by allowing many subscribers to split the cost of a computer. This was done by adapting the operating system (by which the computer coordinates its internal activities) so that it divided the machine's attention among such "tasks" as interacting with a particular user terminal. The computer would flit from one task to the next at intervals ranging from less than a tenth of a second to a second or more, depending on the load of work at the time. Computers became easier to use because they could be reached from a terminal and interrogated in real time. That is, one could now work one's way through a problem by asking a question and using the answer to frame the next question.

Personal computers initially provided services similar to time-sharing, but with much greater convenience. Advances in microprocessors enabled manufacturers to fit a computer on a single chip, making it cheaper to buy a small computer than share a large one. Now that users no longer depended on costly shared facilities, they could work at will on matters that had previously required scheduling. Word processing and chart creation became routine.

As a result, a new class of users was led through a series of increasingly capable software programs, such as spreadsheet applications and page layout aids, that were made practical by the dedication of unprecedented processing power to one individual. Interrogation also became easier because the burden of keeping track of the possible commands shifted from the user to the computer. Now, for example, various choices are displayed in menus and palettes that one can scan visually before pointing out the desired choice.

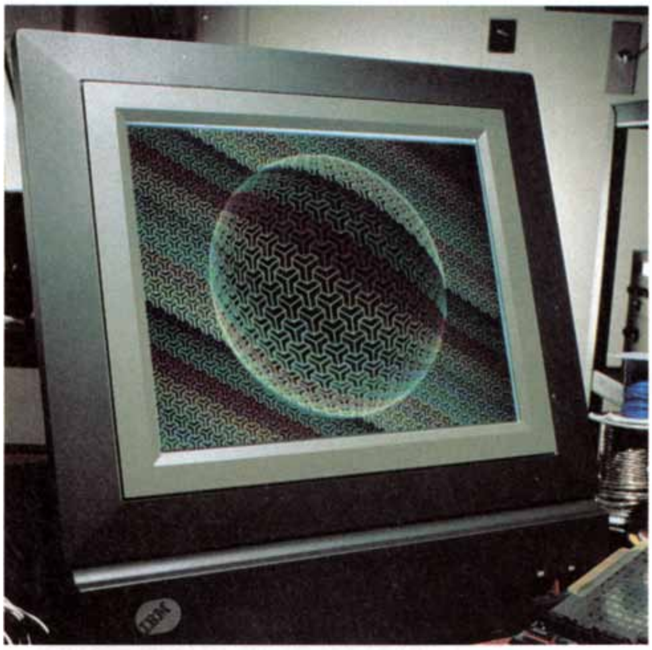
For the millions of people who could afford computing power for the first time, the benefits were compelling. They no longer had to retype a page to add one sentence, wait weeks for others to provide them with typesetting or layout service, make a decision based on one or two tediously calculated financial projections or present an exciting idea in a drab form. The new services began as a luxury but quickly became de rigueur, much as typewriting had a century before.

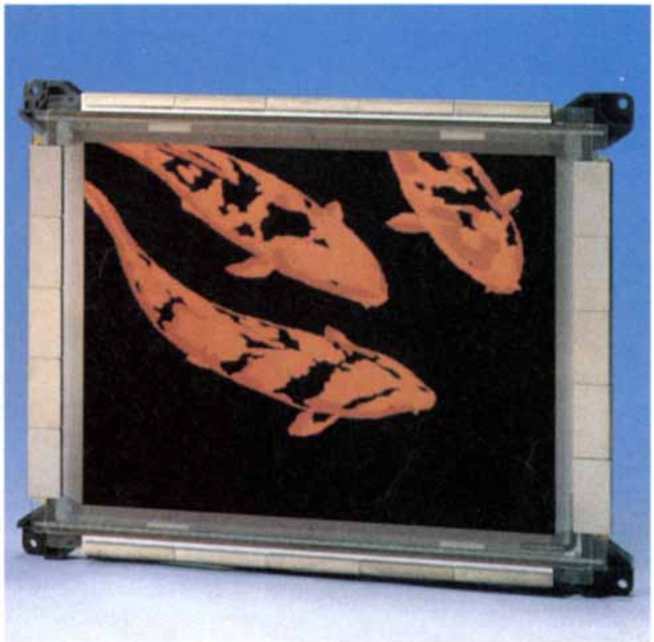
It is important to note that the old paradigms do not necessarily die out completely. In this respect, the evolution of computing recalls that of organisms, which often survive in certain ecological niches even though they have been superseded elsewhere by new forms of life. Time-sharing, for instance, still dominates industries that process many transactions—banking, credit-rating services and airline reservations agencies, for example. New applications have also been developed to take advantage of personal computers. Subscribers



SOURCE: Victor Peterson, NASA Ames

COMPUTING COST has been halved approximately every three years, as indicated in this graph of the most powerful commercial machines of each era.





FLAT SCREENS, such as this liquid-crystal display of IBM (*left*) and this plasma display of Fujitsu (*right*), are considered crucial for the development of compact, portable computers. Future designs will have to consume less power.

can use their modems to dial on-line news, shopping and banking services.

Similarly, the hardware associated with mobile computing will not eliminate desktop computers. A computer plugged into a wall socket quite literally has more power than one operated from batteries. A person working at a desk will have occasion to exploit the larger screen and more capacious storage of a larger machine, as well as the faster and more accurate input of a full-size keyboard. Another continuing advantage of fixed computers lies in the vast amounts of information that can be fed to them. Wires can carry more data than radio waves, and optical fiber—the projected successor to wire—will widen the gap. This edge will be felt in desktop conferencing and other data-hungry video applications.

Every era of computing reflects the contemporary speed of computation, the variety of information that can be processed, the ways computers can be linked into networks, the software by which such networks are exploited and the ways in which humans can interact with the devices. Speed, the most basic element, has improved largely through miniaturization.

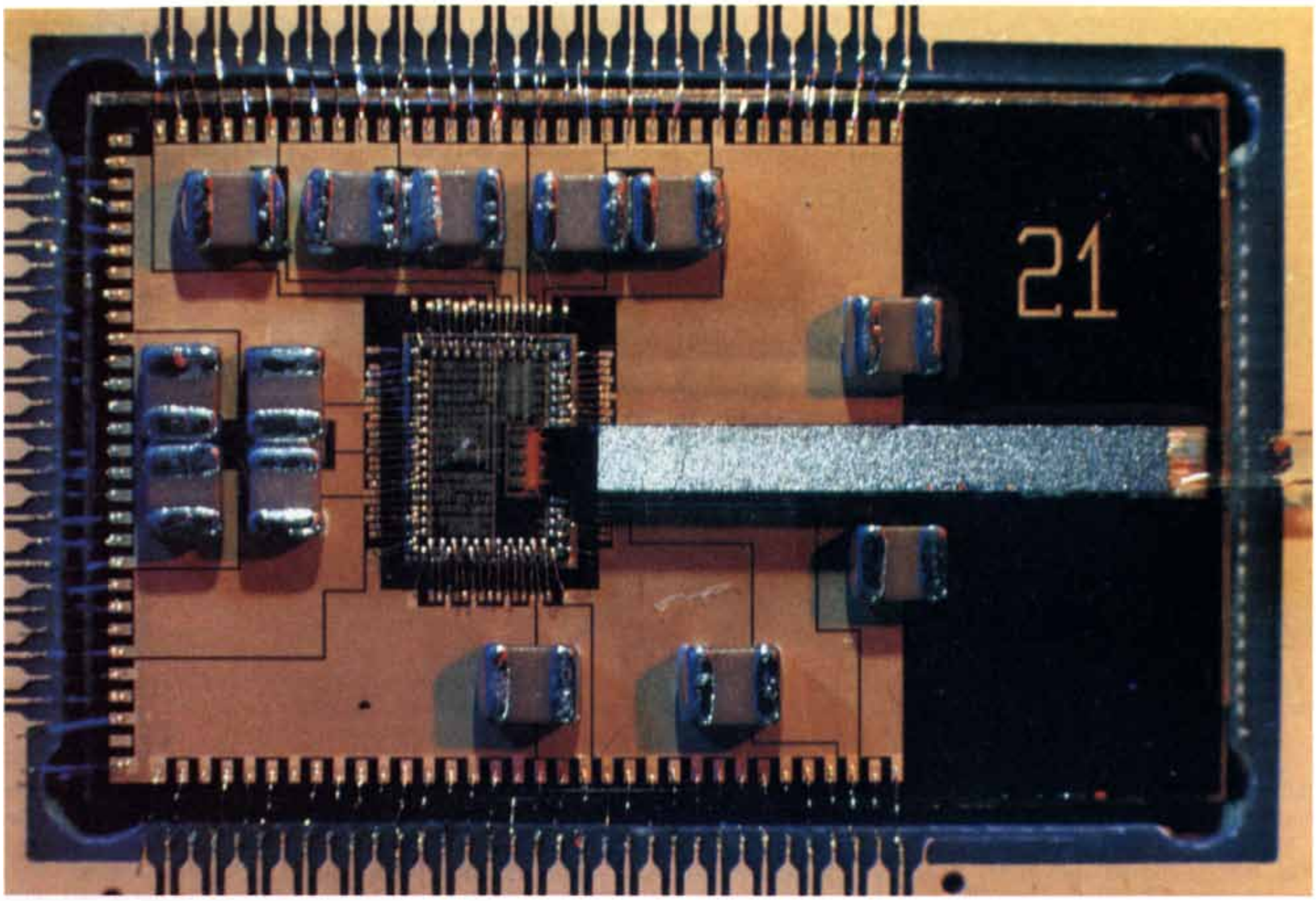
As electronic devices shrink, signals traverse them faster, more operations can be performed in a given period and the cost of computing falls. At the same time, more devices are packed on a chip and thus manufactured in larger batches, reducing the unit cost of manufacturing. Lower costs increase sales, producing additional economies of scale. From the user's point of view, the decline in size yields rapid improvements in usefulness and convenience. Moreover, there is every reason to expect the trend to continue [*see illustration on opposite page*].

Thirty years ago computers were assembled painstakingly out of thousands of transistors and capacitors. Today factories mass-produce computers out of a handful of integrated-circuit chips, each comprising millions of components. In the 1990s, instead of packaging each chip in its own centipedelike, flat package, the semiconductor industry will achieve still higher densities of circuits by producing multichip modules in two and even three dimensions. Stacks of chips will form blocks the size of sugar cubes.

Miniaturization also improves other components of computing systems. Memory, for example, was bulkier than paper as recently as 20 years ago. To store in immediately accessible form a million characters of text (about as many as appear in two copies of this issue of *Scientific American*), one then required a disk pack the size of a birthday cake. By the 1980s that many data could be stored on a diskette that fitted into a shirt pocket. In the 1990s it will be carried on a semiconductor device no larger than a credit card.

New kinds of data become usable with each new paradigm. Early batch-processing systems could manipulate only numbers and uppercase letters. Time-sharing systems made possible interactive document and message editing and often supported vector graphics, which render line drawings on the screen. With personal computers came raster graphics, matrices of dots like the pixels that represent television images. Desktop personal computers already support such media as audio, video, animation and three-dimensional graphics, once the domain of expensive workstations. The coming generation of mobile computers will emphasize facsimile and speech, media that are particularly useful to those who are away from the office.

Networks became important as succeeding paradigms increased the number of computers in service. When batch processors were few, there was little reason to try to make them work in concert. Time-sharing, however, is unthinkable without networks: dedicated or dial-up lines must connect numerous terminals to a host computer, either a corporate mainframe or a departmental minicomputer. The obvious next step was to establish wider networks, among many bank branches, for instance, to make possible the electronic exchange of data. Time-sharing users shared centrally located mass storage facilities and high-speed printers connected to the host. They could post electronic mail messages for other users to see when they next logged in at their terminals. The early terminals were "dumb," that is, they served as mere data links. Lat-



IBM'S EXPERIMENTAL NEXIS CHIP converts signals from optical to electronic form fast enough for computers to exchange data in real time over long distances. Such capabilities will be necessary for advanced networks. The chip integrates four gallium arsenide detectors with the circuitry that amplifies and preprocesses their output signal. The fiber-optic channels (*center*) are made visible by the transmission of red light; infrared light is normally used to minimize energy losses.

er versions incorporated minimal computing power, thus pointing the way to personal computers.

In the desktop computing era, computer networks have assumed new forms. Local-area networks connect personal computers to one another and to shared machines—both general-purpose computers, called hosts, and special-purpose machines, called servers, which provide communal files, high-quality printing and institution-wide electronic mail. Wide-area networks interconnect the various fragments of an enterprise, linking the big machines and file servers to desktop machines. As computers become mobile, wireless connections will proliferate until the information network becomes virtually ubiquitous.

Software applications will also change as mobile computers begin to appear in—or out of—briefcases, purses and pockets. Today's portable machines mainly continue the menu style of interaction, but in the next decade supplementary styles will arise. Transcription software, for example, has already appeared that enables portable machines to display printed versions of handwritten words and polished renderings of roughly drawn figures. Related software recognizes hand-drawn symbols that each represent an entire command or idea. Speech-recognition software that obeys spoken commands is also finding wider application as the technology improves.

Most portable computers now run software written for larger machines, but applications packages are being designed for people who are away from their desks. In such situations, users make notes and sketches but lack the time to compose and edit their jottings. They also exchange information with clients and colleagues, check in with the home office and plan their appointments and how to get to them.

Palmtop machines that perform these functions constitute the first full-fledged pericomputers. So far they cannot compute much, but they suffice for situations into which full-function computers cannot go. One can, for example, work out the day's itinerary on a desktop machine and transfer it to a pericomputer for quick reference. Notes taken in the field can be readied for desktop editing; a pocket calendar and a group calendar can be kept in agreement. Such modest applications will establish a customer base large enough to justify writing a wide range of specialized software. New software will then widen the market.

Software, indeed, will change more than any other element in the computing paradigm. For the first time, it will be written with an eye to the group as well as to the individual. The change reflects the widening of networks, which bring users closer to the work and to one another. It is sometimes hard to remember that until the late 1970s computers were operated by technical experts. They were the trained chefs of the industry: users placed their orders and awaited service. The arrival of personal computers enabled people of all backgrounds to use computers. As in home cooking, more effort was often necessary, but the results, if not always quite up to commercial standards, were at least fully under one's control.

In five or six years' time it will be as natural to collaborate through a network as it is to prepare a holiday feast with friends in a common kitchen. The software that supports group activity is called groupware; the collaborative activity itself has been dubbed Computer-Supported Cooperative Work. CSCW can be conducted in one place or many, at the same or different times: a meeting in a conference room, a video conference involving distant sites, an electronic bulletin board through which workers on different shifts cooperate or an electronic mail system through which an author and an editor exchange drafts.

When the calendars of the members of an organization are kept on a network server, meeting times convenient to them all can be found automatically by groupware such as Meeting Maker, a product designed by ON Technology in Cambridge, Mass. The initiator selects a time and an available room, types in an agenda and transmits it to prospective attendees. The software invites the people, asks them whether they plan to attend and gives them the opportunity to comment. The initiator of the meeting can reschedule the meeting with ease, literally by dragging a visual representation of the event from one part of the calendar to another with a hand-operated mouse or stylus. The system then notifies the participants of the change.

Whereas Meeting Maker enhances the productivity of a group, other groupware goes further by supporting abstract intellectual collaboration. Engineers in different parts of the world, for example, will be able to design together as if they were standing in front of the same chalkboard. Networked computers can simulate many existing collaboration tools and overcome some of their limitations. A computer can keep an accurate record of a dialogue for later reorganization, editing and distribution. It can ease the construction, viewing, modification and presentation of models in three or more dimensions. It can transport drafts by electronic mail so that each participant can quickly make editing changes. It can keep track of who changed what and merge nonconflicting changes automatically.

When everyone in a brainstorming meeting has a computer and all the computers are on a network, ideas can be captured and displayed in a shared space for all to see, either on their separate computers or on a wall-projected display. Experience at the Xerox Palo Alto Research Center and other CSCW research centers has shown that people judge ideas that appear on a screen more for their value than by the rank of the contributor. An added advantage is that people need not wait their turn or even speak up to be heard [see "Computers, Networks and Work," by Lee Sproull and Sara Kiesler, page 116].

Groupware becomes more worthwhile when wireless communications allows users to gain access to it at will. Such access is crucial: people want to form impromptu working groups in any room, whether or not it has network sockets, and they most need access to group calendars when they are away from their desks. When this becomes practical, other needs will become apparent, too. A person on the move or in a meeting cannot stare at a screen or issue detailed instructions, for example, but it is easy to give a brief command to an infinitely patient and obedient software agent.

Groupware and other network software will in many cases succeed or fail on the basis of how many tenths of a second it takes to respond to a user's query. In many cases, limited products will beat sophisticated ones by getting the job done immediately. This will be especially true of active services, such as those provided by software agents, that guide a person's decisions in real time. A driver who wants to change course to avoid a traffic snarl, for example, cannot wait long for directions.

It is not enough that software be quick to please; it must also be easy to obtain. The marketing trend can already be discerned. Personal desktop computing stimulated a market for generic applications with mass-market appeal, with the result that software publishers now routinely distribute their products on "floppy" disks or pocket-size diskettes through retail outlets and by mail order. When software distribution becomes electronic, people will be able to order a product and load it into their computers in a matter of minutes. There will be less temptation to make illegal copies, which many people do to save not money but time.

Electronic software distribution will also lead vendors to package software into smaller units that can be transmitted more easily. Consumers will compose their own applications out of separately acquired software, analogous to the components of a home audio system. The advent of such "component" software will reverse the past decade's trend toward ever larger, more expensive and harder-to-learn applications. Instead of upgrading from last year's word processor with 20 features to this year's version with 40, a customer can select desired features from a catalog. Those who need a new feature will be able to receive it immediately and, in some cases, automatically. Subscribers to the Prodigy service network already do so: their personal computers receive updated software immediately after the subscriber logs onto the service.

Many hurdles must be cleared before the promise of ubiquitous networks can be fully realized. Several hurdles may constitute serious bottlenecks, a problem familiar in the early stages of previous paradigms. Although aspects of personal computing had been predicted many years beforehand, for example, it took technologies such as the single-chip microprocessor and semiconductor DRAM (dynamic random-access memory) as well as many commercial factors to fulfill the predictions by 1980. For mobile networked computing to become mainstream in the 1990s, a number of technologies will have to advance in terms of their speed, weight, size, ruggedness, cost and consumption of electric power.

Compact, power-thrifty video screens are an absolute necessity for pericomputers. Liquid-crystal displays (LCDs) are the current standard, although they are only now beginning to match cathode-ray tubes in quality. One approach that promises to solve the problem, pioneered independently by RCA Laboratories and by Westinghouse Laboratories, switches liquid-crystal elements so that they polarize light, thus directing it to the proper color filter. Color LCDs and their fluorescent backlights, however, place a major load on the portable battery. New technologies that emit light directly from the screen may provide alternatives that consume less power. One candidate is the field-emission display, which incorporates thousands of microscopic cathodes.

The power drain of a portable computer's electronics places one of the most important constraints on its performance. The devices that require the least power are therefore attracting the most interest. Among them are chips made according to the process of complementary metal oxide semiconductors (CMOSs); systems that operate at a low voltage (say, 3.3 volts, instead of the standard five volts); circuits that employ few chips, thus lessening the charge on interchip wiring; and architectures that use a slow system clock (which paces all components the way a conductor paces an orchestra).

The two most promising architectures wring more speed from less power in quite different ways. One is called RISC (reduced instruction set computer) because it transfers much work from the hardware to software. Yet most available RISC architectures have been of limited use in mobile machines because they have been designed to optimize performance, not to minimize size and power consumption. One exception is the design of ARM Ltd of Cambridge, England.

The other approach avoids the trade-off between clock speed and power consumption by jettisoning the clock. Such data-flow, or asynchronous, architectures were originally designed to aid in the field of parallel processing. They schedule each processing step to begin only when the necessary data become available. But just-in-time computing introduces great complexities. It is rather like running an orchestra whose members get their cues from one another, rather than from a conductor.

If power is at a premium, one might also try to improve the batteries. The weaknesses of current batteries include the lack of reusability of alkaline designs, the low capacity of nickel-cadmium batteries and the bulk of lead-acid batteries. These weaknesses can sometimes be offset. Miniaturization has improved capacitors, for instance, so that they can accumulate power from low-output sources and supply it in periods of high demand. Software has also been used to drain power automatically from nickel-cadmium batteries before each recharge, thereby averting a permanent loss of storage capacity (or so-called memory effect). New batteries based on nickel-metal hydride and lithium also offer great promise, as do photovoltaic cells, which are already used in calculators. Unfortunately, the conservation of energy makes it impossible for any manageable array of solar cells to supply a backlight bright enough to overcome the sun's glare.

The technologies of handwriting and speech recognition are important because they make mobile computers easier to use. That mission must always be kept in mind; otherwise, one may be tempted to judge a system solely by the number of words it can distinguish or the percentage of errors it makes. Handwriting recognition has been touted for bringing computers into the lives of people who do not like to type. Even those who do like to type cannot do so when standing or holding a machine. In Japan, where the language has a profusion of written symbols that keyboards cannot easily handle, the technology is considered a key selling point.

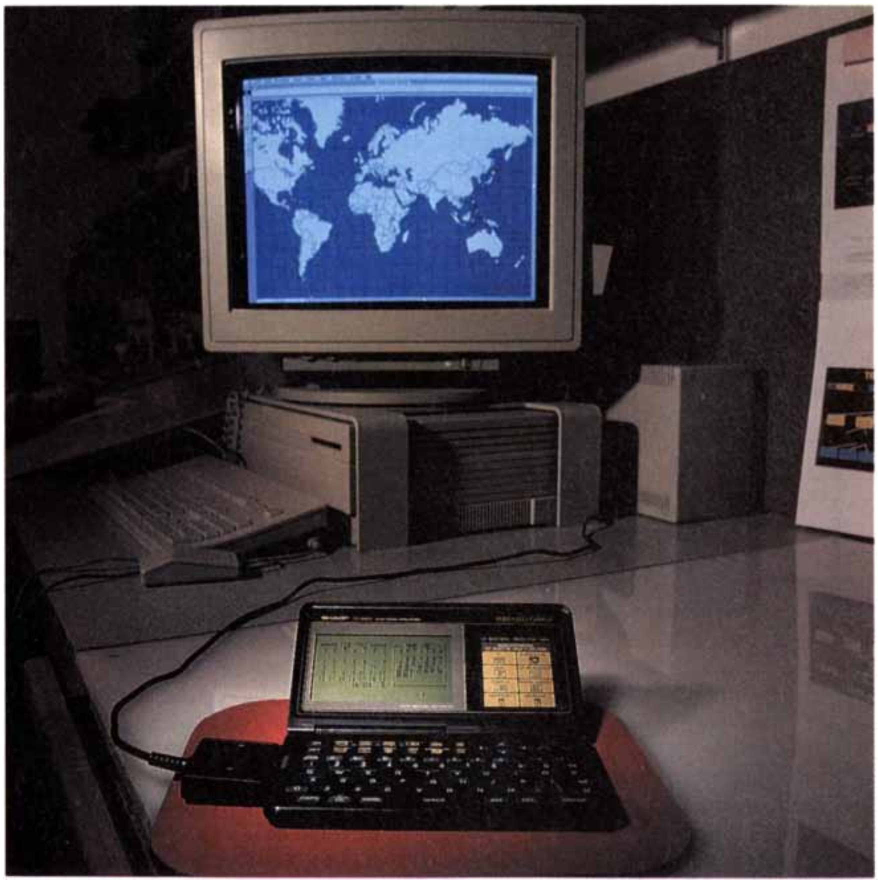
Experience gained with handwriting recognition will be valuable because it can, to some extent, be transferred to speech recognition. Both technologies require, in the more sophisticated applications, a detailed linguistic analysis by which the software raises its chance of recognizing a word or phrase. Both face the challenge of finding where one word ends and the next one begins. Finally, both must be trainable, so that they can adapt their representations of letters or sounds to the handwriting and pronunciation of the user.

Versatile speech recognition requires substantial computing power, but lesser hardware can provide limited capabilities that often prove useful. It is hard to program any computer to take continuous dictation without mistaking the end of one word for the beginning of the next. But it is easy to program even a hand-held computer to distinguish "yes" from "no." A handful of commands may be all most users need to utter when their hands are not free. It has been shown, for example, that mail sorters become much more productive when they call out zip codes instead of dropping their work to fill out a form. Yet this application requires that the system distinguish only 10 words: those for the numerals.

Recognition systems can identify a stroke of the stylus or a trill of the voice by analyzing it into a set of features. Such features can then be compared against a template stored in the computer's memory. Alternatively, the features can be analyzed by neural networks, so called because they mimic the way in which the brain is believed to work. A computer links a digital representation of neurons into a network, then selectively changes the weights assigned to each connection. A process of trial and error then "trains" the system to distinguish various signals.

Another technical challenge to wireless pericomputers is the capacity of the electromagnetic medium itself. To prevent one transmitter from drowning out another, networks within a given building will group transmitters into cells as small as a room. Larger cells will require radio, although local ones may choose infrared light because it uses a part of the electromagnetic spectrum that is not regulated by federal and international authorities.

The limited carrying capacity of that spectrum was exemplified about 10 years ago, when the vogue for citizens band (CB) radio collapsed of its own



PERSONAL ORGANIZER brings networks to the palm of one's hand. These mobile devices can be downloaded directly (*as shown above*) or by telephone.

MASTER AND MAN: the image of the computer has changed with its mode of use. When the machines were expensive and hard to program, they were portrayed as remote tyrants, as in the 1970 movie *Colossus: The Forbin Project*. In this scene, Dr. Forbin is shown leaning against Colossus, the computer that he designed and by which he is finally mastered. Will tomorrow's computer be able to play the benign role of the ideal personal servant—at once ubiquitous and inconspicuous?

weight when users could no longer make themselves heard above the din. Yet that crunch on band space will seem as nothing once mobile computers start blasting megabytes of data across the ether. Even the adoption of a system of cellular relays, such as the one now used for car telephones, might not defer saturation for more than a few years.

Cellular systems will in any case be necessary because mobile machines have to be tracked as they move. If two collaborating users get out of range, the network will have to reestablish the connection transparently through intermediary routing equipment. Even so, there will be times when mobile devices lose contact. Software must therefore be designed so that people affected can easily resume interrupted communication.

No less important than the changes in technology are their human effects. Every new paradigm has molded the way users perceive their status in relation to the computer. In batch and time-sharing days, many users felt subservient; desktop computers gave them independence; mobile networked computers will bring them freedom.

The networked computer will thus challenge not only business but also society. Universal connectivity raises issues of security and personal and business privacy. It also raises the question of the distribution of power. The chasms between rich and poor could widen, for example, if the latest computing paradigm creates still more opportunities for educated people and still fewer for the uneducated.

For reasons of social equity and economic efficiency, it will become more important than ever to educate all people so that they can benefit equally from the information resources that are about to become available. Should the benefits of networks become general, democracy might well be enhanced. Such a pattern can be discerned in Eastern Europe, where the recent revolutions appear to have been helped along by the presence of personal computers, copiers and facsimile transmitters.

The computer, then, has changed much since the days when the movies portrayed it as a relentless superbrain, extending its tyranny to all the world. Its popular image has also changed, albeit with a slight lag. Yet the day is not distant when mobile computers will be common in movies and movie sets alike, where they will manage everything from the scriptwriter's 23rd draft to the key grip's accumulating overtime pay. In that day, art will catch up to life, and the computer will take on a new persona.

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