Beyond Moore's Law

If semiconductor manufacturing goes on obeying Moore's Law, PCs by 2050 will be performing a billion billion (quintillion: 10^{18}) operations per second and holding as many bytes in their memories. Indeed, researchers at the University of Minnesota announced in January that they had found a way to store a single electron in a 7-nanometer-square semiconductor, a density that would put 2.55 quadrillion (10^{15}) bytes on a 1-centimeter-square chip. If this happens in the next few years, it will have the effect of accelerating the Law by about 30 years.

Even if Moore's Law ends tomorrow, we can coast for decades, creating myriads of products that exploit the near-term projection of densities and phenomena, such as chips that hold living organisms. By themselves, super-PCs are not very interesting. The most valuable lodes to be mined from greater component densities will come from developments in three areas: platforms, networks that interconnect them, and the ability to interact with human beings and real-world information systems.

To put all this in context, it is useful first to consider alternative pathways of development for super-PCs. Back in 1975 I posited these three evolutionary paths:

- Constant or slightly lower prices and increasing performance.
- Much lower prices, with costs falling by an order of magnitude about every 10 years, creating new kinds of computers.
- The commodification of functions into microsystems-on-a-chip.

Since the '70s, most new classes of computer systems have developed along the second path. Thus US \$100 000 minicomputers emerged in the '70s to rival \$1 million mainframes that had been introduced in 1951; in the '80s we got \$20 000 workstations and \$2000 PCs; in the '90s it is personal organizers and personal digital assistants for \$100–\$500 and electronic dictionaries for even less.

We are now at a crossroads at which it is possible to take the third evolutionary path. Continuing on the path of miniaturizing mainframes will be to bypass the opportunity to create new classes of products that will dramatically enhance the universal usefulness of computing systems. We can start by developing new sensors and transducers that interface with other real-world systems. Already in development are new classes of computers with new operating platforms to exploit the advantages of global networks. Employing client-server architecture along with browser software, we are on the threshold of introducing low-cost hybrid television-telephone access to the World Wide Web.

Computer systems on a chip now appear inevitable following the announcement last September that 36 computer and semiconductor firms had formed an alliance to build such a system. This development will create a huge new microsystems industry with a market potential at least two orders of magnitude greater than the PC industry. Every PC will be connected to thousands of other systems, all built around a single-chip architecture, with its interconnection bus also on a chip. Each microsystem will contain a processor, memory hierarchy, I/O capability (including speech), and standards-compliant platform software. With more-powerful processors, firmware (software on a ROM) will replace hardware.

The table shows the evolution of computer classes in the context of the foregoing analysis, assuming that Moore's Law continues to hold. —*C. Gordon Bell*

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1. Evolution of computer classes and components

Year	Generation	Platform	User interface	Network
1951	Direct and batch use	Computer, vacuum tube, transistor, core, drum, magnetic tape	Card, paper tape direct control evolving to batch op system	None (originally stand-alone computers)
1965	Interactive timesharing via commands; minicomputers	Integrated circuit, disk, minicomputer; multiprogramming	Glass teletype and keypunch, control by command language	Telephone using modem, and proprietary wide-area networks
1981	Distributed PCs and workstations	Microprocessor PCs, workstations, floppy, small disk, distributed operating system	WIMP (windows, icons, mouse, pull-down menus)	Wide- and local-area networks
1994	World Wide Web access through PCs and workstations	Evolutionary PCs and workstations, servers everywhere, Web op system	Browser	Optical-fiber backbone, World Wide Web, hypertext transfer protocol
1998	Web computers: network, telephone, TV computers	Client software from server using JAVA, ActiveX, and so forth	Telephone, simple videophone, television access to the web	Subscriber digital lines for telephone or cable access for high-speed data
1998	SNAP: scalable network and platforms	PC uni- or multiprocessor commodity platform	To multimedia Web clients	System area network for clusters
2001	"Do what I say" speech-controlled computers	Embedded in PCs, hand-held devices, phones, digital assistants	Speech	Infrared and radio LANs for network access
2010	One info dial tone: phone, videophone, TV, and data	Video-capable devices of all types	Video as a primary data type	Single high-speed network access; home net
2020	Anticipatory by "observing" user behavior	Room monitoring, gesture	Vision, gesture control	Home Net
2025	Body Net: vision, hearing, monitoring, control, communication, location	Artificial retina, cochlea, glasses for display, monitoring and recording of everything we see, hear, and say	Implanted sensors and actuators for virtually every part of a body	Body Network, gateway to local IR or radio nets everywhere. Humans are part of cyberspace
2048	Robots for home, office, and factory	General-purpose robot; appliances become robotic	Radar, sonar, vision, mobility, arms, hands	IR and radio LAN for home and local areas