Introduction

Information technology (IT) is a manifestation of public and private investment in science and engineering (S&E) that is enabling broad and significant changes in society. Many observers (Drucker 1999; Alberts and Papp 1997; Castells 1996; Freeman, Soete, and Efendioglu 1995; Kranzberg 1989) compare the rapid development and expansion of IT to the industrial revolution in terms of its potential scope and impact on society. Few other modern advances in technology have had the capacity to affect so fundamentally the way people work, live, learn, and govern themselves. As with the industrial revolution, both the time and direction of many of the changes are difficult to predict.

The relationship between IT and S&E has two aspects. In addition to being a product of S&E, IT is enabling changes in S&E. IT has become an important part of the overall U.S. investment in research and development (R&D) and affects how R&D is conducted in all disciplines. For example, scientists and engineers make extensive use of computer modeling and simulation and large shared databases; advances in networking facilitate global collaboration in research and product development; and IT producers employ scientists and engineers, implement the results of academic research, and conduct significant amounts of applied R&D. IT also influences the pipeline for S&E through its effects on the demand for people with technical skills and through its use in education at all levels.

This chapter addresses IT as a leading example of the effects of investment in S&E on society and focuses on IT as a major force underlying changes in the S&E enterprise.

A complete discussion of the impact of IT on society and the economy is beyond the scope of this chapter because IT has become integrated into nearly all aspects of society, from entertainment to national security. Moreover, in recent years, other government publications (Council of Economic Advisers 2001; U.S. Department of Commerce (DOC) 2000a,b) have begun to cover important aspects of the digital economy. References and notes in this chapter direct the reader to some of these other more detailed sources.

The chapter begins with a description of trends in IT and then discusses some major implications of IT, including effects on the economy and the general public. Finally, it discusses the effects of IT on elements of the S&E system, including R&D, innovation processes, higher education, and the IT workforce.

Trends in IT

IT, as defined in this chapter, reflects the combination of three key technologies: digital computing, data storage, and the ability to transmit digital signals through telecommunications networks. Rapid changes in semiconductor technology, information storage, and networking, combined with advances in software, have enabled new applications, cost reductions, and the widespread diffusion of IT. The expanding array of applications makes IT more useful and further fuels the expansion of IT.

Semiconductor Technology

Enormous improvements in the performance of integrated circuits and cost reductions brought about by rapid miniaturization have driven much of the advances in IT. See sidebar, "Moore's Law."

A related trend is the migration of computing into other devices and equipment. This is not a new trend—automobiles have been major users of microprocessors since the late 1970s—but as semiconductor chips become more powerful and less expensive, they are becoming increasingly ubiquitous. Also, new capabilities are being added to chips. These include microelectromechanical systems (MEMs), such as sensors and actuators, and digital signal processors that enable cost reductions and extend IT into new types of devices.[1] Examples of MEM devices include ink-jet printer cartridges, hard disk drive heads, accelerometers that deploy car airbags, and chemical and environmental sensors (Gulliksen 2000). Trends toward improvements in microelectronics and MEMs are expected to continue. See sidebar, "Nanoscale Electronics."

Information Storage

Disk drives and other forms of information storage reflect similar improvements in cost and performance. (See figure 8-2.) As a consequence, the amount of information in digital form has expanded greatly. Estimates of the amount of original information (excluding copies and reproductions) suggest that information on disk drives now constitutes the majority of information (Lyman and Varian 2000). (See appendix table 8-2.) Increasingly, much of this information is available on-line.

Computers, reflecting the improvements in their components, have shown similar dramatic improvements in performance. Due to improvements in semiconductors, storage, and other components, price declines in computers (adjusted for quality) have actually accelerated since 1995. (See figure 8-3.)

Networking

The third trend is the growth of networks. Computers are increasingly connected in networks, including local area networks and wide area networks. Many early commercial computer networks, such as those used by automated teller machines and airline reservation systems, used proprietary systems that required specialized software or hardware (or both). Increasingly, organizations are using open-standard, Internet-based systems for networks.[2] As people have been

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[1]Related terms are microstructure technologies or microsystem technologies (MSTs). To some, MSTs include all chips that have noncomputing functions (such as sensors or actuators), whereas MEMs are the subset of MSTs that have moving parts (Gulliksen 2000).

[2]The Internet, as defined by the Federal Networking Council, refers to the global information system that "(i) is logically linked together by a globally unique address space based on the Internet Protocol (IP) or its subsequent extensions/follow-ons; (ii) is able to support communications using the Transmission Control Protocol/Internet Protocol (TCP/IP) suite or its subsequent extensions/follow-ons and/or other IP-compatible protocols; and (iii) provides, uses, or makes accessible—either publicly or privately—high level services layered on the communications and related infrastructure described herein" (Kahn and Cerf 1999).

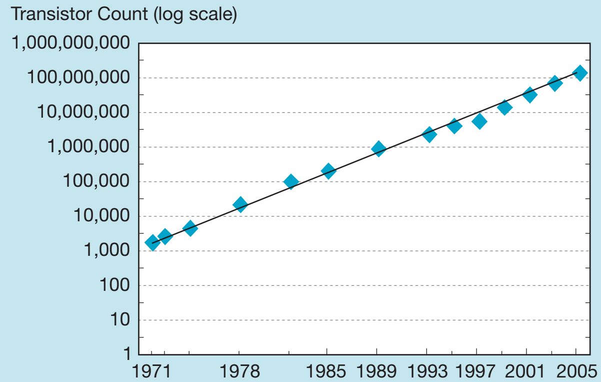
Moore's Law

The number of transistors on a chip has doubled approximately every 12 to 18 months for the past 30 years—a trend known as Moore's Law. (See figure 8-1 and appendix table 8-1.) This trend is named for Gordon Moore of Intel, who first observed it. Performance has increased along with the number of transistors per chip, while the cost of chips has remained generally stable. These factors have driven enormous improvements in the performance/cost ratio.

Moore's Law has become the basis for planning in the semiconductor industry. The International Technology Roadmap for Semiconductors (2000), a plan for semiconductor development prepared collaboratively by semiconductor industries around the world, is geared toward continuing improvements at approximately the rate predicted by Moore's Law.

Kurzweil (2001) suggests that this trend is not limited to semiconductors in the last few decades but that calculations per second per dollar have been increasing exponentially since electromechanical calculators were introduced in the early 1900s.

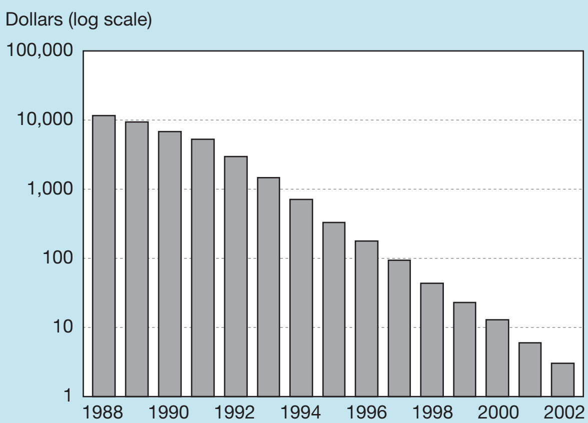
Figure 8-1.
Moore's Law: 1971–2005



NOTES: The line on the graph represents the trend that defines Moore's Law. The data points reflect actual (1971–2001) and projected (2003–2005) data.

See appendix table 8-1. *Science & Engineering Indicators – 2002*

Figure 8-2.
Cost per gigabyte of stored information: 1988–2002



NOTES: 2001 and 2002 data are projected.

SOURCE: P. Lyman and H. R. Varian. 2000. "How Much Information?" Available at <http://www.sims.berkeley.edu/how-much-info/>. Accessed July 2, 2001.

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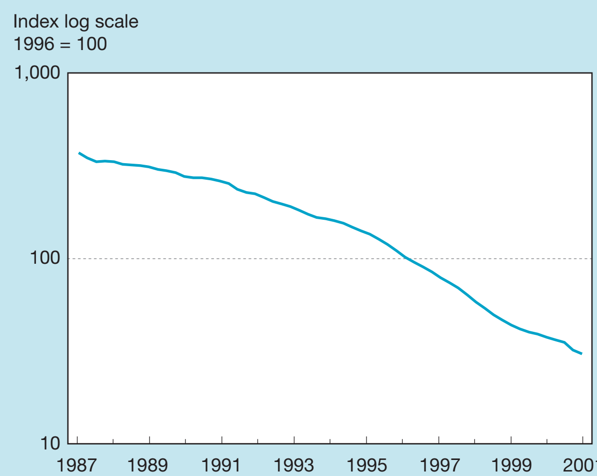
Figure 8-3.
Computer price declines



SOURCE: U.S. Department of Commerce, Bureau of Economic Analysis, National Accounts Data. Available at <http://www.bea.doc.gov/bea/dn1.htm>.

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able to interconnect and share information with each other, the value of IT has increased. See sidebar, "Metcalfe's Law."

The growth in networking has been enabled by rapid advances in optical networking. In 1990, a single optical fiber could transmit about 1 billion bits per second; by 2000, a single fiber could transmit nearly 1 trillion bits per second (Optoelectronics Industry Development Association 2001).

The growth in networking is best illustrated by the rapid growth of the Internet. Worldwide, there were nearly 100 million Internet hosts—computers connected to the Internet—in July 2000, up from about 30 million at the beginning of 1998. (See figure 8-4.) Networking is evolving in several ways: more people and devices are becoming connected to the network,

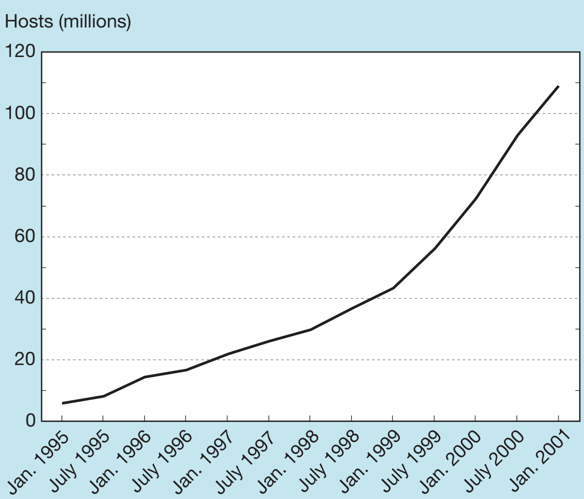
Nanoscale Electronics

As miniaturization proceeds, it may lead to the emergence of nanoscale devices (devices with structural features in the range of 1 to 100 nanometers). The International Technology Roadmap for Semiconductors (2000) projects semiconductor manufacturing to approximately 2010, at which time semiconductors are expected to have 0.1-micron (100-nanometer) structures. Beyond this, the principles, fabrication methods, and ways of integrating devices into systems are generally unknown. Potential applications of nanoscale electronics 10–15 years in the future include (National Science and Technology Council 2000):

- microprocessor devices that continue the trend toward lower energy use and cost per gate, thereby improving the efficacy of computers by a factor of millions;
- communications systems with higher transmission frequencies and more efficient use of the optical spectrum to provide at least 10 times more bandwidth, with consequences for business, education, entertainment, and defense;
- small mass storage devices with capacities at multiterabit levels, 1,000 times better than today; and
- integrated nanosensor systems capable of collecting, processing, and communicating massive amounts of data with minimal size, weight, and power consumption.

Such advances would continue to expand the cost effectiveness and utility of IT in new applications.

Figure 8-4.
Internet domain survey host count worldwide



SOURCE: Internet Software Consortium (<http://www.isc.org>).

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the speed and capacity of connections are increasing, and more people are obtaining wireless connections. See sidebar, "Wireless Networking."

Applications of IT

A fourth trend is the ever-increasing array of applications that make IT more useful. Computers were originally used primarily for data processing. As they became more powerful and convenient, applications expanded. Word processing, spreadsheets, and database programs were among the early minicomputer and PC applications. Over the past two decades, innovations in software have enabled applications to expand to include educational software, desktop publishing, computer-aided design and manufacturing, games, modeling and simulation, networking and communications software, electronic mail, the World Wide Web, digital imaging and photography, audio and video applications, electronic commerce applications, groupware, file sharing, search engines, and many others. The growth and diversity of applications greatly increase the utility of IT, leading to its further expansion.

In the 1960s, computers were used primarily in the R&D community and in the offices of large companies and agencies. Over the past few decades, the expansion of applications has contributed to the rapid diffusion of IT to affect nearly everyone, not just the relatively few people in computer-intensive jobs. IT has become common in schools, libraries, homes, offices, and businesses. For example, corner grocery stores use IT for a variety of electronic transactions such as debit and credit payments, and automobile repair shops use IT to diagnose problems and search for parts from dealers. New IT applications are still developing rapidly; for example, instant messaging and peer-to-peer communication systems such as Napster are examples that have become popular in the past 2 years. See sidebar, "Peer-to-Peer Applications."

Societal Implications

In contrast to the steady and rapid advances in semiconductor technology, information storage, networking, and applications, the interaction of IT with various elements of society is more complex. Although IT performance in many cases improves exponentially, the utility to users in many cases improves more slowly (Chandra et al. 2000). For example, a doubling of computer processing speeds may bring only small improvements in the most widely used applications, such as word processing or spreadsheets. Furthermore, although it is common to talk about the "impact" or "effect" of IT or the Internet—implying a one-way influence—the interaction of IT with society is multidirectional and multidimensional. Over the past two decades, many studies have explored how organizations use IT. Cumulatively, these studies have found that a simple model of IT leading to social and organizational effects does not hold (Kling 2000). Instead, IT is developed and used in a social context in which organizations and individuals shape the technology and the way it is used. The implementation of IT is an ongoing social process that involves