1 Understanding the Information Age

1.1 Faster, Better, Cheaper

Modern information technology begins with the invention of the *transistor*, a semiconductor device that acts as an electrical switch and encodes information in binary form. A binary digit or *bit* takes the values zero and one, corresponding to the off and on positions of a switch. The first transistor, made of the semiconductor germanium, was constructed at Bell Labs in 1947 and won the Nobel Prize in Physics in 1956 for the inventors—John Bardeen, Walter Brattain, and William Shockley.[1]

The next major milestone in information technology was the co-invention of the *integrated circuit* by Jack Kilby of Texas Instruments in 1958 and Robert Noyce of Fairchild Semiconductor in 1959. An integrated circuit consists of many, even millions, of transistors that store and manipulate data in binary form. Integrated circuits were originally developed for data storage and retrieval and semiconductor storage devices became known as *memory chips*.[2]

The first patent for the integrated circuit was granted to Noyce. This resulted in a decade of litigation over the intellectual property rights. The litigation and its outcome demonstrate the critical importance of intellectual property in the development of information technology. Kilby was awarded the Nobel Prize in Physics in 2000 for discovery of the integrated circuit; regrettably, Noyce died in 1990.[3]

1.1.1 Moore's Law

In 1965 Gordon Moore, then Research Director at Fairchild Semiconductor, made a prescient observation, later known as *Moore's Law*.[4]

Plotting data on memory chips, he observed that each new chip contained roughly twice as many transistors as the previous chip and was released within 18–24 months of its predecessor. This implied exponential growth of chip capacity at 35–45 percent per year! Moore's prediction, made in the infancy of the semiconductor industry, has tracked chip capacity for 35 years. He recently extrapolated this trend for at least another decade.[5]

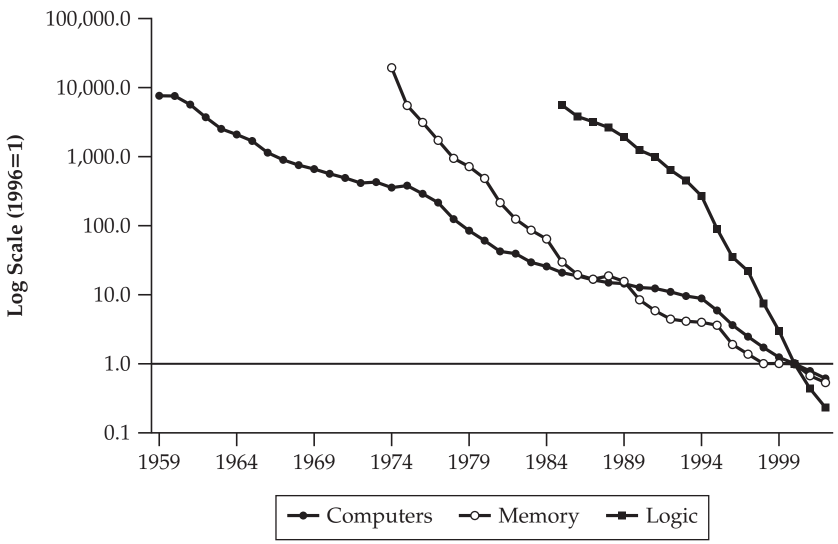
In 1968 Moore and Noyce founded Intel Corporation to speed the commercialization of memory chips.[6] Integrated circuits gave rise to *microprocessors* with functions that can be programmed by software, known as *logic chips*. Intel's first general purpose microprocessor was developed for a calculator produced by Busicom, a Japanese firm. Intel retained the intellectual property rights and released the device commercially in 1971.

The rapidly rising trends in the capacity of microprocessors and storage devices illustrate the exponential growth predicted by Moore's Law. The first logic chip in 1971 had 2,300 transistors, while the Pentium 4 released on November 20, 2000, had 42 million! Over this 29-year period the number of transistors increased by 34 percent per year. The rate of productivity growth for the U.S. economy during this period was slower by two orders of magnitude.

1.1.2 Semiconductor Prices

Moore's Law captures the fact that successive generations of semiconductors are *faster* and *better*. The economics of semiconductors begins with the closely related observation that semiconductors have become *cheaper* at a truly staggering rate! Figure 1.1 gives semiconductor price indexes constructed by Bruce Grimm (1998) of the Bureau of Economic Analysis (BEA) and employed in the U.S. National Income and Product Accounts since 1996. These are divided between memory chips and logic chips. The underlying detail includes seven types of memory chips and two types of logic chips.

Between 1974 and 1996 prices of memory chips *decreased* by a factor of 27,270 times or at 40.9 percent per year, while the implicit deflator for the gross domestic product (GDP) *increased* by almost 2.7 times or 4.6 percent per year! Prices of logic chips, available for the shorter period 1985 to 1996, *decreased* by a factor of 1,938 or 54.1 percent per year, while the GDP deflator *increased* by 1.3 times or 2.6 percent per year! Semiconductor



Note: All price indexes are divided by the output price index.

Figure 1.1
Relative prices of computers and semiconductors, 1959–2002.

price declines closely parallel Moore's Law on the growth of chip capacity, setting semiconductors apart from other products.

Figure 1.1 also reveals a sharp acceleration in the decline of semiconductor prices in 1994 and 1995. The microprocessor price decline leapt to more than 90 percent per year as the semiconductor industry shifted from a three-year product cycle to a greatly accelerated two-year cycle. This is reflected in the *2003 Edition* of the International Technology Road Map for Semiconductors,[7] prepared by a consortium of industry associations. Ana Aizcorbe, Stephen Oliner, and Daniel Sichel (2003) have identified and analyzed break points in prices of microprocessors and storage devices.

1.1.3 Constant Quality Price Indexes

The behavior of semiconductor prices is a severe test for the methods used in the official price statistics. The challenge is to separate observed price changes between changes in semiconductor performance and changes in price that hold performance constant. Achieving this objective has required a detailed understanding of the technology, the development of sophisticated measurement techniques, and the introduction of novel methods for assembling the requisite information.

Ellen Dulberger (1993) introduced a "matched model" index for semiconductor prices. A matched model index combines price relatives for products with the same performance at different points of time. Dulberger presented constant quality price indexes based on index number formulas, including the *Fisher* (1922) *ideal index* used in the in the U.S. national accounts.[8] The Fisher index is the geometric average of the familiar Laspeyres and Paasche indexes.

Erwin Diewert (1976) defined a *superlative* index number as an index that *exactly* replicates a *flexible* representation of the underlying technology (or preferences). A flexible representation provides a second-order approximation to an arbitrary technology (or preference system). A. A. Konus and S. S. Byushgens (1926) first showed that the Fisher ideal index is superlative in this sense. Laspeyres and Paasche indexes are not superlative and fail to capture substitutions among products in response to price changes accurately.

Grimm (1998) combined matched model techniques with hedonic methods, based on an econometric model of semiconductor prices at different points of time. A hedonic model gives the price of a semiconductor product as a function of the characteristics that determine performance, such as speed of processing and storage capacity. A constant quality price index isolates the price change by holding these characteristics of semiconductors fixed.[9]

Beginning in 1997, the Bureau of Labor Statistics (BLS) incorporated a matched model price index for semiconductors into the Producer Price Index (PPI) and since then the national accounts have relied on data from the PPI. Reflecting long-standing BLS policy, historical data were not revised backward. Semiconductor prices reported in the PPI prior to 1997 do not hold quality constant, failing to capture the rapid semiconductor price decline and the acceleration in 1995.

1.1.4. Computers

The introduction of the Personal Computer (PC) by IBM in 1981 was a watershed event in the deployment of information technology. The sale of Intel's 8086-8088 microprocessor to IBM in 1978 for incorporation into the PC was a major business breakthrough for Intel.[10] In 1981 IBM licensed the MS-DOS operating system from the Microsoft

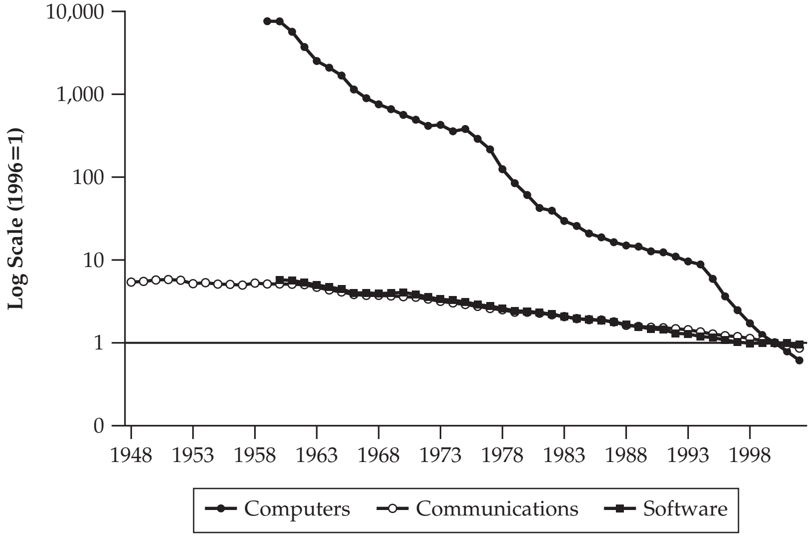
Corporation, founded by Bill Gates and Paul Allen in 1975. The PC established an Intel/Microsoft relationship that has continued up to the present. In 1985 Microsoft released the first version of Windows, its signature operating system for the PC, giving rise to the Wintel (Windows-Intel) nomenclature for this ongoing collaboration.

Mainframe computers, as well as PCs, have come to rely heavily on logic chips for central processing and memory chips for main memory. However, semiconductors account for less than half of computer costs and computer prices have fallen much less rapidly than semiconductor prices. Precise measures of computer prices that hold product quality constant were introduced into the NIPA in 1985 and the PPI during the 1990s. The national accounts now rely on PPI data, but historical data on computers from the PPI, like the PPI data on semiconductors, do not hold quality constant.

Gregory Chow (1967) pioneered the use of hedonic techniques for constructing a constant quality index of computer prices in research conducted at IBM. Chow documented price declines at more than 20 percent per year during 1960–1965, providing an initial glimpse of the remarkable behavior of computer prices. In 1985 the Bureau of Economic Analysis incorporated constant quality price indexes for computers and peripheral equipment constructed by IBM into the NIPA. Jack Triplett's (1986) discussion of the economic interpretation of these indexes brought the rapid decline of computer prices to the attention of a very broad audience.

The BEA-IBM constant quality price index for computers provoked a heated exchange between BEA and Edward Denison (1989), one of the founders of national accounting methodology in the 1950's and head of the national accounts at BEA from 1979 to 1982. Denison sharply attacked the BEA-IBM methodology and argued vigorously against the introduction of constant quality price indexes into the national accounts.[11] Allan Young (1989), then Director of BEA, reiterated BEA's rationale for introducing constant quality price indexes.

Dulberger (1989) presented a more detailed report on her research on the prices of computer processors for the BEA-IBM project. Speed of processing and main memory played central roles in her model. Triplett (1989, 2003) has provided exhaustive surveys of research on hedonic price indexes for computers. Gordon (1989, 1990) gave an alternative model of computer prices and identified computers and communications equipment, along with commercial aircraft, as assets with the highest rates of price decline.



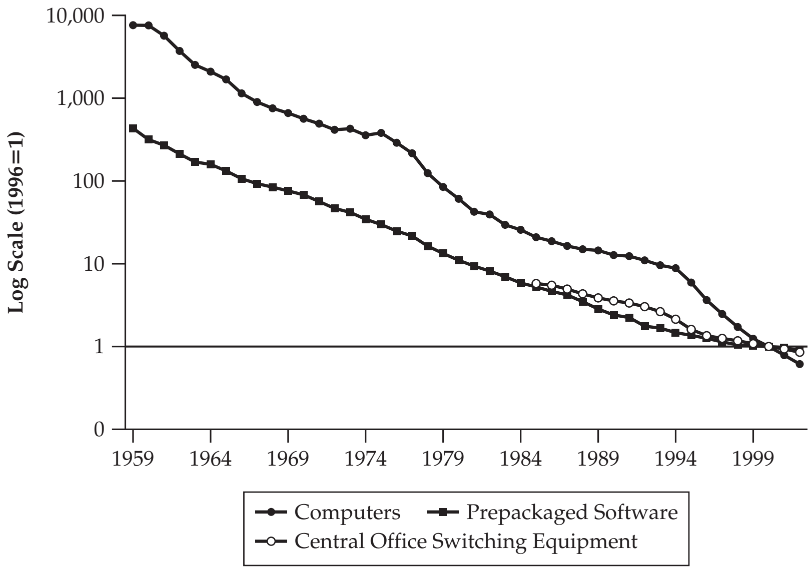
Note: All price indexes are divided by the output price index.

Figure 1.2
Relative prices of computers, communications, and software, 1948–2002.

Figure 1.2 gives BEA's constant quality index of prices of computers and peripheral equipment and its components, including mainframes, PCs, storage devices, other peripheral equipment, and terminals. The decline in computer prices follows the behavior of semiconductor prices presented in Figure 1.1, but in much attenuated form. The 1995 acceleration in the computer price decline parallels the acceleration in the semiconductor price decline that resulted from the changeover from a three-year product cycle to a two-year cycle in 1995.

1.1.5 Communications Equipment and Software

Communications technology is crucial for the rapid development and diffusion of the Internet, perhaps the most striking manifestation of information technology in the American economy.[12] Kenneth Flamm (1989) was the first to compare the behavior of computer prices and the prices of communications equipment. He concluded that the communications equipment prices fell only a little more slowly than computer prices. Gordon (1990) compared Flamm's results with the official price indexes, revealing substantial bias in the official indexes.



Note: All price indexes are divided by the output price index.

Figure 1.3
Relative prices of computers, central office switching equipment, and prepackaged software, 1959–2002.

Communications equipment is an important market for semiconductors, but constant quality price indexes cover only a portion of this equipment. Switching and terminal equipment rely heavily on semiconductor technology, so that product development reflects improvements in semiconductors. Grimm's (1997) constant quality price index for digital telephone switching equipment, given in figure 1.3, was incorporated into the national accounts in 1996. The output of communications services in the NIPA also incorporates a constant quality price index for cellular phones.

Much communications investment takes the form of the transmission gear, connecting data, voice, and video terminals to switching equipment. Technologies such as fiber optics, microwave broadcasting, and communications satellites have progressed at rates that outrun even the dramatic pace of semiconductor development. An example is dense wavelength division multiplexing (DWDM), a technology that sends multiple signals over an optical fiber simultaneously. Installation of DWDM equipment, beginning in 1997, has doubled the transmission capacity of fiber optic cables every 6 to 12 months.[13]

Mark Doms (2005) has provided comprehensive price indexes for terminals, switching gear, and transmission equipment. These have been incorporated into the Federal Reserve's Index of Industrial Production, as described by Carol Corrado (2003), but are not yet included in the U.S. National Income and Product Accounts. The analysis of the impact of information technology on the U.S. economy described below is based on the national accounts and remains incomplete.

Both software and hardware are essential for information technology and this is reflected in the large volume of software expenditures. The eleventh comprehensive revision of the national accounts, released by BEA on October 27, 1999, re-classified computer software as investment.[14] Before this important advance, business expenditures on software were treated as current outlays, while personal and government expenditures were treated as purchases of nondurable goods. Software investment is growing rapidly and is now much more important than investment in computer hardware.

Parker and Grimm (2000) describe the new estimates of investment in software. BEA distinguishes among three types of software—prepackaged, custom, and own-account software. Prepackaged software is sold or licensed in standardized form and is delivered in packages or electronic files downloaded from the Internet. Custom software is tailored to the specific application of the user and is delivered along with analysis, design, and programming services required for customization. Own-account software consists of software created for a specific application. However, only price indexes for prepackaged software hold performance constant.

Parker and Grimm (2000) present a constant quality price index for prepackaged software, given in figure 1.3. This combines a hedonic model of prices for business applications software and a matched model index for spreadsheet and word processing programs developed by Oliner and Sichel (1994). Prepackaged software prices decline at more than ten percent per year over the period 1962–1998. Since 1998 the BEA has relied on a matched model price index for all prepackaged software from the PPI; prior to 1998 the PPI data do not hold quality constant.

BEA's prices for own-account and custom software are based on programmer wage rates. This implicitly assumes no change in the productivity of computer programmers, even with growing investment in hardware and software to support the creation of new software. Custom and own-account software prices are a weighted average of prepackaged software prices and programmer wage rates with arbitrary weights of 75 percent for programmer wage rates and 25 percent for prepackaged software. These price indexes do not hold the software performance constant and present a distorted picture of software prices, as well as software output and investment.

1.2. Economic Impact of Information Technology

We now consider the "killer application" of the new framework for productivity measurement—the impact of information technology (IT) on economic growth. Despite differences in methodology and data sources, a consensus has emerged that the remarkable behavior of IT prices provides the key to the surge in U.S. economic growth after 1995. The relentless decline in the prices of information technology equipment and software has steadily enhanced the role of IT investment. Productivity growth in IT-producing industries has risen in importance and a productivity revival is underway in the rest of the economy.

A substantial acceleration in the IT price decline occurred in 1995, triggered by a much sharper acceleration in the price decline of semiconductors, the key component of modern information technology. Although the decline in semiconductor prices has been projected to continue for at least another decade, the recent acceleration may be temporary. This can be traced to a shift in the product cycle for semiconductors from three years to two years as a consequence of intensifying competition in markets for semiconductor products.

In chapter 3 we show that the surge of IT investment in the United States after 1995 has counterparts in other industrialized countries. It is essential to use comparable data and methodology in order to provide rigorous international comparisons. A crucial role is played by measurements of IT prices. The U.S. national accounts have incorporated measures of IT prices that hold performance constant since 1985. Schreyer (2000) has extended these measures to other industrialized countries by constructing "internationally harmonized prices".[15]

We show that the acceleration in the IT price decline in 1995 triggered a burst of IT investment in all of the G7 nations—Canada, France, Germany, Italy, Japan, the U.K., as well as the U.S. These countries also experienced a rise in productivity growth in the IT-producing industries. However, differences in the relative importance of these industries have generated wide disparities in the impact of IT on economic growth. The role of the IT-producing industries is greatest in the U.S., which leads the G7 in output per capita.

In chapters 4 through 8 we trace the American growth resurgence to the sources within the individual industries that make up the U.S. economy. For this purpose we have constructed measures of output and productivity for 44 industry groups. A novel feature of this data set is that output and productivity for the four IT-producing industries—semiconductors, computers, communications equipment, and software—can be separately identified at a detailed level not previously available. We divide the remaining 40 industries between 17 IT-using industries, those that are particularly intensive in the utilization of information technology equipment and software, and 23 non-IT industries.

Chapter 8 presents a framework for decomposing the sources of aggregate growth among industries. The gross domestic product (GDP) is the sum of value-added over the 44 industries. Equivalently, GDP is the sum of expenditures on final demands—consumption, investment, and net exports. In chapters 2 and 3 we have used the expenditure definition of GDP to provide a "top down" perspective on the sources of growth for the economy as a whole. In chapter 8 we have employed the value-added definition of GDP to give a "bottoms up" perspective that incorporates the sources of growth for individual industries. This is based on a production possibility frontier that gives the value-added for each of the 44 industries as a function of the inputs of capital and labor services into the U.S. economy.

The expenditure approach employed in chapter 2 and the industry value-added approach in chapter 8 provide similar views of the American growth resurgence. The expenditure approach presents a concise overview of the U.S. economy without requiring detailed data for individual industries. The value-added approach characterizes the sources of growth for individual industries, while providing a great deal of supporting detail for the sources of growth at the aggregate level. This approach makes it possible to trace the ramifications of rapid price declines for information technology equipment and software for each of the 44 industries that make up the U.S. economy.

Altogether, 31 of the 44 industries contribute to the acceleration in U.S. economic growth after 1995. The four IT-producing industries are responsible for only 2.9 percent of the GDP but a quarter of the U.S. growth resurgence. The 17 IT-using industries account for another quarter of the surge in growth and about the same proportion of the GDP, while the Non-IT industries with 70 percent of value added are responsible for half the resurgence. The contribution of the IT-producing industries is far out of proportion to their relatively small size. These industries have grown at double-digit rates throughout the period 1977–2000, but their growth jumps sharply after 1995, when the GDP share of these industries also increases.

Turning to the sources of the growth acceleration after 1995, we find that the contribution of capital input is the most important, total factor productivity is next, and the contribution of labor input is almost negligible. The acceleration in capital input growth is primarily in information technology and software, reflecting the surge of IT investment after 1995, especially in the large IT-using sectors like Finance. Virtually all industries respond to the acceleration in the decline of prices of IT capital input after 1995 by substituting IT for non-IT capital inputs and nearly half of U.S. industries show a declining contribution of non-IT capital input.

The four IT-producing industries contributed more to the growth of total factor productivity during the period 1977–2000 than all other industries combined. In fact, the contributions of the IT-using and non-IT industries were slightly negative during this period, partly offsetting the positive contribution of the IT-producing industries. After 1995 the IT-producing industries show sharply accelerating growth in total factor productivity, while the IT-using industries diverge from this trend by exhibiting a more rapid decline. Total factor productivity growth in the non-IT industries jumps very substantially, accounting for most of the acceleration in productivity.

In chapter 8 we document the contributions of individual industries to the U.S. growth resurgence. This is broken down between the contributions of capital and labor inputs and the acceleration in total factor productivity growth. Industries from all three groups—IT-producing, IT-using, and non-IT—are important sources of the acceleration in U.S. economic growth. The IT-producing industries show accelerated growth in every dimension, but the impact is limited by their relatively small size. The IT-using sectors are especially prominent in the exploitation of opportunities for accelerated deployment of IT equipment and software, while the non-IT industries contribute impressively to faster productivity growth.

Chapter 7 analyzes the sources of growth for individual industries within the U.S. economy. At the industry level the value of output is defined as the sum of value-added, consisting of capital and labor inputs, and the value of intermediate inputs. This definition of output has the crucial advantage that the role of intermediate goods and services, such as inputs of semiconductors into the IT-producing industries, can be clearly identified. Total factor productivity is defined as output per unit of input, where input includes capital, labor, and intermediate inputs. It is important to emphasize that this study is the first to measure total factor productivity growth, as well as growth of all three inputs, for the four IT-producing industries.

Output growth rates are by far the most rapid for the IT-producing industries. While industry output is an aggregate of value-added and intermediate input, it is nonetheless remarkable that IT-producing sectors have the most rapid growth of both intermediate inputs and value-added. Two industries responsible for much of IT hardware—Computers and Office Equipment and Electronic Components—exhibit truly extraordinary rates of productivity growth throughout the period 1977–2000 as well as a substantial acceleration after 1995. However, the acceleration in productivity growth characterizes 28 of the 41 industries for which we measure productivity at the industry level, so that the productivity surge is very widespread.

Data for output and intermediate inputs presented in chapter 7 are taken from chapter 4, data for capital input from chapter 5, and data for labor input from chapter 6. The rapid growth of the four IT-producing industries has its sources in rapid growth of inputs and productivity, although the relative importance of these sources differs considerably. All the IT-producing industries have large contributions of intermediate inputs, including inputs from other IT-producing sectors. Computers and electronic components have large growth rates of productivity, while computer services, containing software, has a large contribution of labor input, but no productivity growth.

We find considerable variation in total factor productivity growth across industries and over time. More than half of the industries in this study show both positive and negative growth in productivity during the period 1977–2000, which is not consistent with the view that negative total factor productivity growth is only an indication of errors in the measurement of output. No doubt there are such errors, but negative productivity growth has many other explanations. We also find that intermediate inputs predominate in gross output for about 70 percent of the industries, so that output rather than value-added should be the primary focus in analyzing the sources of growth at the industry level. We provide a breakdown of intermediate inputs between IT and non-IT products to provide additional insight into the contribution of information technology equipment and software.

We find that accelerated growth of IT capital input after 1995 characterizes 37 of our 41 private industries, so that the shift toward investment in IT equipment and software in response to more rapid IT price declines emerges very visibly at the industry level. Although the contribution of college-educated labor predominates over non-college labor for most of the period 1977–2000 and most industries, only about a third of the industries show acceleration in the growth of college-educated labor after 1995. The strong economy of the late 1990s drew many workers with relatively low skills and limited experience into employment.

Chapter 4 provides data on industry output and intermediate input, based on a time series of input-output tables developed by the Employment Projections Branch of the Bureau of Labor Statistics. We also provide data on value-added, defined as output less intermediate input. This approach was introduced by Jorgenson, Gollop, and Fraumeni (1987) and conforms to the international standards of best practice for productivity measurement presented by Schreyer (2001). We employ value-added, as well as capital and labor inputs, in analyzing the sources of growth in GDP at the industry level. We use inputs of intermediate inputs, as well as capital and labor services, in analyzing the sources of growth in industry outputs.

Investment in IT products is the most important mechanism for diffusion of advances in the underlying technology. The ongoing declines in the prices of these products provide powerful incentives for investment. The key to understanding the diffusion mechanism is the cost of capital, an annualization factor useful in converting asset prices to rental prices of capital inputs. The cost of capital depends on asset-specific rates of revaluation and depreciation, as well as the tax treatment of income from the asset. In chapter 5 we present prices of capital input for all industries, classified by asset type and form of ownership, which determines the tax treatment. These estimates are based primarily on the BEA reproducible assets accounts and conform to the international standards presented by Blades (2001).

The most distinctive features of IT assets are the rapid declines in prices of the assets, as well as relatively high rates of depreciation. These characteristics imply that rental prices of IT capital inputs are very large in comparison to the prices of IT capital assets. We find that capital inputs from IT products have grown at double-digit rates during the period 1977–2000 with a median growth rate of 19.11 percent. By contrast non-IT capital inputs have growth at a median rate of

2.17 percent. The substantial acceleration in the growth of capital input after 1995 can be traced to the change in composition associated with the growing importance of information technology.

Chapter 6 presents measures of labor input by industry. We classify hours worked and labor compensation per hour by gender, class of employment, age, and education. The primary data sources are the Current Population Survey (CPS) and the decennial Census of Population; however, the data are benchmarked to the U.S. National Income and Product Accounts (NIPAs). We also provide a detailed decomposition of the components of the growth of labor quality, defined as the ratio of labor input to hours worked. Quality captures the shift in hours worked toward workers with higher rates of compensation, reflecting higher marginal products. Labor quality growth is dominated by the increased education and experience of workers, offsetting a smaller decline in quality due to rising female participation.

Computer Services, containing software, is the most rapidly growing industry in terms of labor input during the period 1977–2000. The very modest acceleration in the growth of labor input after 1995 was concentrated in IT-using industries. Since the number of workers available for employment is determined largely by demographic trends, the impact of the acceleration in IT investment is reflected mainly in rates of labor compensation and changes in the industry distribution of employment. The rapidly growing IT-using industries have absorbed large numbers of college-educated workers, while non-IT industries have shed substantial numbers of non-college-educated workers. Rates of labor compensation rise primarily for the young.

Notes

1. On Bardeen, Brattain, and Shockley, see: http://www.nobel.se/physics/laureates/1956/.
2. Charles Petzold (2000) provides a general reference on computers and software.
3. On Kilby, see: http://www.nobel.se/physics/laureates/2000/. On Noyce, see: Tom Wolfe (2000), pp. 17–65.
4. Moore (1965). Vernon Ruttan (2001), pp. 316–367, provides a general reference on the economics of semiconductors and computers. On semiconductor technology, see: http://euler.berkeley.edu/~esrc/csm.
5. Moore (2003).
6. Moore (1996).
7. On International Technology Roadmap for Semiconductors (2003), see: http://public.itrs.net/.
8. See Steven Landefeld and Robert Parker (1997).

9. Triplett (2004) has written a manual for the OECD on constructing constant quality price indexes for information technology and communications equipment and software.
10. See Moore (1996).
11. Denison cited his 1957 paper, "Theoretical Aspects of Quality Change, Capital Consumption, and Net Capital Formation," as the definitive statement of the traditional BEA position.
12. General references on the economics of the Internet are Soon-Yong Choi and Andrew Whinston (2000) and Robert Hall (2002). On Internet indicators see: http://www.internetindicators.com/.
13. Rick Rashad (2000) characterizes this as the "demise" of Moore's Law. Jeff Hecht (1999) describes DWDM technology and provides a general reference on fiber optics.
14. Brent Moulton (2000) describes the 11th comprehensive revision of NIPA and the 1999 update.
15. The measurement gap in IT prices between the U.S. and other OECD countries was first identified by Andrew Wyckoff (1995).