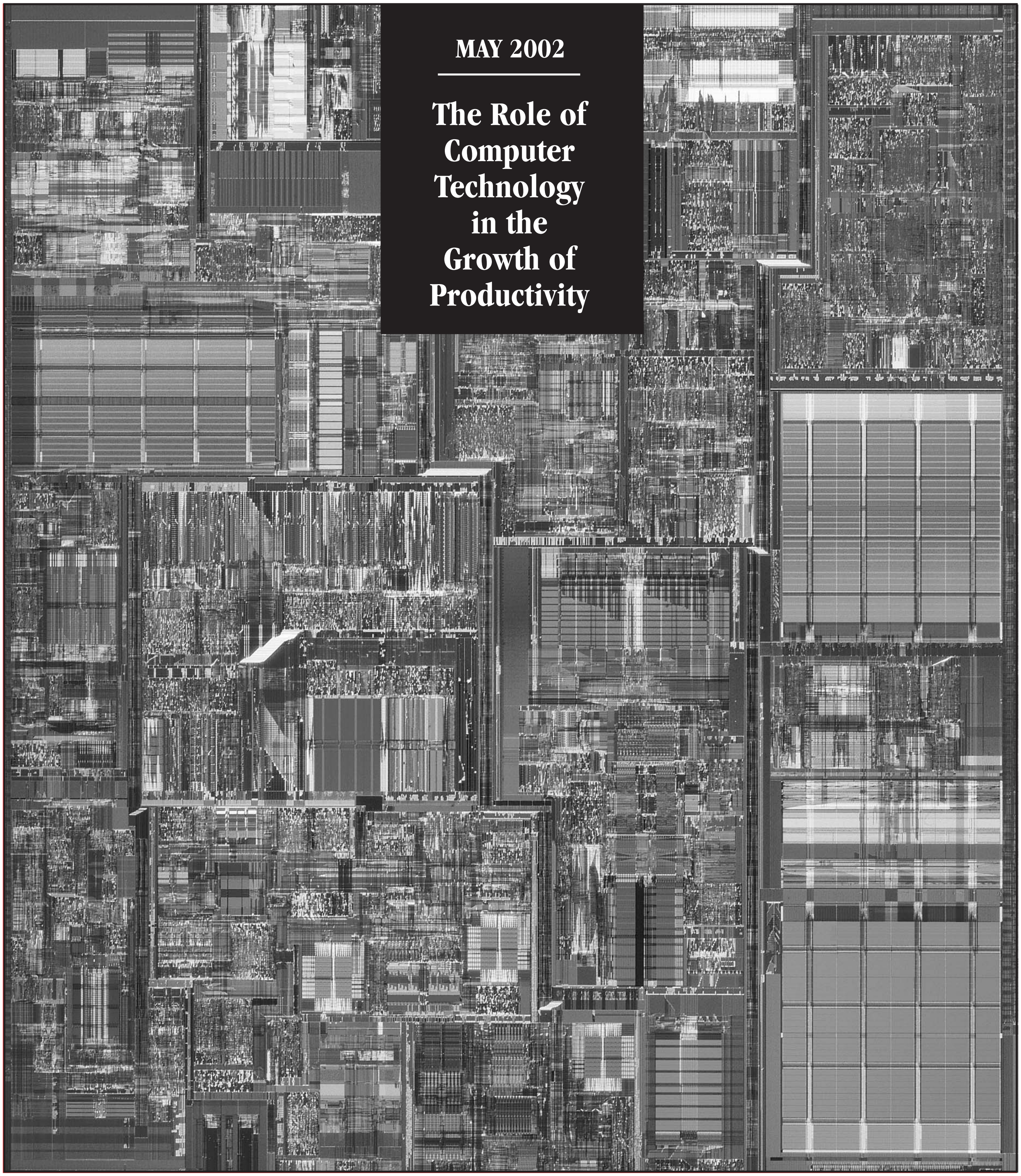
CONGRESS OF THE UNITED STATES
CONGRESSIONAL BUDGET OFFICE

A CBO PAPER

MAY 2002

The Role of Computer Technology in the Growth of Productivity



THE ROLE OF COMPUTER TECHNOLOGY IN THE GROWTH OF PRODUCTIVITY

May 2002

The Congress of the United States
Congressional Budget Office

NOTES

Numbers in the text and tables may not add up to totals because of rounding.

The cover photo of an Intel Pentium 4 microprocessor appears courtesy of Intel Corporation.

PREFACE

Semiconductor and computer makers achieved remarkable productivity gains in the late 1990s, providing increasingly capable computers to businesses and consumers at ever lower prices. That manufacturing performance was so exceptional that it boosted the growth of national productivity substantially. Looking forward, many observers wonder whether the semiconductor and computer industries will continue to help productivity increase as rapidly as they have in the recent past. This Congressional Budget Office (CBO) paper—prepared at the request of the Senate Budget Committee—reviews the recent productivity growth in the economy, its relationship to improvements in computer technology, and the prospects for such growth and improvements in the future. In keeping with CBO's mandate to provide objective, impartial analysis, this report makes no recommendations.

Nathan Musick and Philip Webre of CBO's Microeconomic and Financial Studies Division prepared the paper under the supervision of Roger Hitchner and David Moore. The paper benefited from comments from Ana Aizcorbe and Dan Sichel of the Board of Governors of the Federal Reserve System, Robert Doering of Texas Instruments, Dale Jorgenson of Harvard University, and Jack Triplett of the Brookings Institution. Within CBO, Bob Arnold, Arlene Holen, Kim Kowalewski, Deborah Lucas, and John Peterson provided useful comments. Bob Arnold also provided productivity estimates. Kathryn Winstead helped with the figures.

John Skeen edited the manuscript, and Christine Bogusz proofread it. Angela Z. McCollough prepared the paper for publication, and Annette Kalicki produced the electronic versions for CBO's Web site (www.cbo.gov).

Dan L. Crippen
Director

May 2002

CONTENTS

SUMMARY vii

I INTRODUCTION 1

II MEASURING POTENTIAL TOTAL FACTOR PRODUCTIVITY 7

The Basics of Growth Accounting *7*
The Contribution of Computer Hardware Manufacturing to the Acceleration of Total Factor Productivity Growth in the Late 1990s *9*
The Accuracy of Growth-Accounting Results Amid Economic and Technological Change *13*

III PRICES OF COMPUTERS AND COMPONENTS 17

The Technology Trajectory and Market Swings *17*
The Impact of Decreases in Component Prices on Computer Prices in the Late 1990s *20*
Trends in the Manufacture of Computer Systems *23*

IV THE TECHNOLOGICAL OUTLOOK AND ITS IMPLICATIONS FOR THE NEXT DECADE 27

Technological Trends for Integrated Circuits *27*
Technological Trends for Disk Drives *32*
Future Trends in the Demand for Computers *33*
Implications for Total Factor Productivity Growth *35*

APPENDIX A: HEDONIC PRICE ESTIMATION 39

TABLES

S-1. Contributions to Potential Total Factor Productivity Growth in the Nonfarm Business Sector, 1951-2012 ix

1-1. Contributions to Potential Growth in the Nonfarm Business Sector, 1951-2012 2

2-1. Percentage Changes in the Price and Quantity of Private Fixed Investment in Computers and Peripheral Hardware, 1991-2000 11

2-2. Nominal Share of Computers and Peripheral Equipment in Gross Domestic Product, 1991-2000 11

2-3. The Computer Hardware Sector's and Other Sectors' Contributions to the Recent Acceleration of Total Factor Productivity Growth 13

3-1. Price Declines for Computer Components Compared with Those for Complete Computer Systems, 1995-2000 21

4-1. Effects of Different Paths for Computer Prices on Total Factor Productivity, 2002-2012 37

FIGURES

3-1. Prices for Dynamic Random Access Memory, 1978-2000 19

4-1. Wholesale Prices for Disk Drives, 1980-2000 33

BOXES

4-1. Technological Challenges in Fabricating Integrated Circuits 30

A-1. An Example of Hedonic Price Estimation in the Producer Price Index 41

SUMMARY

Because federal revenues and expenditures are closely tied to the performance of the U.S. economy, the reliability of the Congressional Budget Office's (CBO's) 10-year budget projections depends heavily on the accuracy of its economic projections. The most pertinent measure of future economic activity is potential gross domestic product (GDP), which is the highest level of economic activity that could occur without raising the rate of inflation.

During the latter half of the 1990s, CBO and other forecasters underestimated the growth of potential GDP. The primary cause of that inaccuracy was growth in the contributions of capital inputs and of potential total factor productivity (TFP) —growth that was surprisingly rapid from a historical perspective.[1] According to most analysts, advances in computer technology caused a large part of that acceleration in potential TFP growth. Similarly, those advances reduced the cost of business investment in computer and peripheral equipment, thereby boosting the contribution of capital inputs to potential GDP growth. So those two sources of growth at unexpected levels were closely related. Looking forward, in order to make projections, analysts must determine if computer technology will continue to improve as rapidly in the future and if it is likely to be a major influence on the rate of potential TFP growth.

RECENT TRENDS IN THE GROWTH OF POTENTIAL TOTAL FACTOR PRODUCTIVITY AND ITS RELATION TO COMPUTER TECHNOLOGY

Until very recently, economists found little evidence that computers had contributed to the growth of potential total factor productivity. In spite of the prominence of ever improving computer systems at ever lower prices, which suggests sizable TFP gains in semiconductor and computer manufacturing, the slowdown in total factor productivity growth that began in the early 1970s continued through the first half of the 1990s.

1. Capital inputs are the structures and equipment used in production. Potential TFP is the portion of the growth in potential GDP that is over and above what can be attributed to the use of capital and labor; it is often linked to technological progress.

However, starting in the mid-1990s, quality-adjusted computer prices began to fall more rapidly than they had previously, and investment in computers began to rise more rapidly than it had previously. Increased purchases of computers meant that the share of GDP devoted to computer investment climbed. Because productivity growth in the computer industry was higher than in most other industries, as its share of GDP rose, so did the weighted average productivity of the economy. After factoring out the impact of procedural changes made by U.S. statistical agencies in the mid-1990s, CBO attributes all of the acceleration in potential TFP growth during the 1996-2001 period to technological advances in the production of computer hardware—that is, computer-related semiconductors and computer equipment, including peripheral equipment (see Summary Table 1).

In contrast to such a conclusion about semiconductor and computer *manufacturing*—a conclusion that is generally shared by many analysts—no consensus exists yet on the degree to which computer *use* has boosted total factor productivity growth. The emergence of a "new economy," characterized by economic benefits from the application of information technology (computer hardware, software, and communications equipment) that exceed the returns expected from the use of other types of capital, remains, at least for the present, a topic of debate.

Over the past several decades, economists have worked to incorporate the increases in computer purchases and the improvements in computer technology in the national income and product accounts (produced by the Bureau of Economic Analysis) and other economic measures. Computers purchased today are far more powerful than the ones purchased a few years ago or even last year. New models offer faster processor chips, more memory, and generally more capabilities than earlier vintages. Despite those quality increases, computer purchase prices are often the same or lower than those for older models—hence, direct price comparisons do not reflect the quality improvements that consumers enjoy; only quality-adjusted price comparisons would do so. In such cases, economists use a quality-adjustment procedure known as hedonic price estimation.

Basically, that method allows federal statistical agencies to determine how much extra value consumers place on improvements in computers' features, such as processor speed, and reflect that additional value in official U.S. price indexes. Because those indexes are used in estimating GDP, hedonic price methods also allow technological change in computers and other products to be captured in the national statistics on economic growth. Without those advances in federal statistical techniques, economists would have missed much of the rise in productivity induced by computer hardware manufacturing in the late 1990s.

SUMMARY TABLE 1. CONTRIBUTIONS TO POTENTIAL TOTAL FACTOR PRODUCTIVITY GROWTH IN THE NONFARM BUSINESS SECTOR, 1951-2012 (In percent)

	Average Annual Growth					
	Historical Periods					Forecast
	1951-1973	1974-1981	1982-1990	1991-1995	1996-2001	2002-2012
Potential TFP	2.0	0.8	1.0	1.1	1.3	1.3
Trend TFP	2.0	0.7	1.1	1.1	1.1	1.1
TFP adjustments	0	0	0	0	0.3	0.2
Computer quality	0	0	0	0	0.2	0.1
Price measurement[a]	0	0	0	0	0.1	0.2
Security Costs	0	0	0	0	0	-0.1[b]

SOURCE: Congressional Budget Office, *The Budget and Economic Outlook: Fiscal Years 2003-2012* (January 2002).

NOTE: TFP = total factor productivity.

a. In the early 1990s, the Bureau of Economic Analysis (BEA) made changes to the price indexes it uses to estimate the real output of hospital and physicians' services. Those changes created a discontinuity in the growth rates for those series, as the new price indexes showed much slower rates of increase than the old ones did. Because BEA was not able to apply those revisions retroactively, there is a slight discontinuity in measures of real (inflation-adjusted) gross domestic product and productivity between the 1996-2001 period and earlier years. In calculating potential GDP and potential TFP, CBO carries forward the effect of that new method of measuring. For example, the table shows that those changes accounted for an increase of 0.1 percentage points in the growth rate of potential TFP in the 1996-2001 period.

b. Increased security costs for private businesses in the wake of the attacks of September 11, 2001, are expected to reduce TFP growth across the 2002-2012 period; such expenditures will divert some capital and labor away from their previous uses to producing output, in the form of heightened security, that is not counted in gross domestic product.

Advances in computer technology and the resulting quality-adjusted decline in computer prices occurred through two principal avenues: through increases in the technological capabilities of the components of computers and through increased productivity in the manufacture of computers. The relative importance of each factor is difficult to quantify because of limitations of the data collected by the Bureau of the Census. But depending on the assumptions made about the value of semi-conductors in the manufacture of computer systems, decreases in the quality-adjusted prices of semiconductors and computer storage systems (mainly disk drives) alone accounted for as much as two-thirds of the total drop in the quality-adjusted prices of computers during the latter half of the 1990s.

ADVANCES IN COMPUTER TECHNOLOGY AND FUTURE GROWTH IN TOTAL FACTOR PRODUCTIVITY

Three independent phenomena combined to produce the rapid price declines in computers and components of the late 1990s: the underlying historical rate of price decline driven by technological change; transitory factors, such as the Asian currency crisis, that complemented the other factors in their downward pressure on prices; and changes in market structure that have accentuated price and technological competition in both computer systems and components. Over the next decade, the technology of computer components is likely to continue to improve, as advances in both semiconductors and disk drives face no underlying impediments. Only the transitory factors seem likely to abate in the foreseeable future. Consequently, productivity in the computer industry should grow faster than it did through 1995 but less rapidly than during the 1996-2001 time frame.

As noted earlier, the contribution of computers to overall total factor productivity growth depends not just on the speed of technological advances in computer hardware manufacturing but also on the share of computers in total output (in the form of either consumer, business, or government purchases or net exports). For example, the smaller the share of computers in total output, the smaller the potential impact of technological progress in the computer sector on TFP growth in the economy overall.

CBO forecasts a drop in the share of computers in total output compared with the average share during the latter half of the 1990s. During those years, purchases of computers were particularly high because of the emergence of the Internet and spending on the so-called Y2K problem. With those factors gone, that drop in share and the slower growth of productivity in the computer industry will reduce the amount that gains in potential total factor productivity in computer hardware manufacturing contribute to overall TFP growth in the economy—from 0.2 percent during the 1996-2001 period to 0.1 percent over the 2002-2012 projection period.

CHAPTER I
INTRODUCTION

Because federal revenues and expenditures are closely tied to the performance of the U.S. economy, the reliability of the Congressional Budget Office's (CBO's) budget projections depends heavily on the accuracy of its economic forecasts. The most pertinent measure of future economic activity is potential gross domestic product (GDP), which is the highest level of economic activity that could occur without raising the rate of inflation. CBO's 10-year projections of real (inflation-adjusted) GDP are based on its estimates of the level of potential GDP.

During the latter half of the 1990s, CBO and other forecasters underestimated the growth of real GDP and, as a consequence, had to revise upward their estimates of the growth in potential GDP. For example, CBO projected real GDP growth to increase by 2 percent annually in the 1996-2000 period. In fact, that growth averaged 4.1 percent.[2] As a result, CBO has raised its estimate of the growth in potential GDP to 3.9 percent annually between 1996 and 2001 (see Table 1-1).

An important factor explaining the underestimates of potential GDP growth during the late 1990s was growth in the contributions of capital inputs and potential total factor productivity (TFP)—growth that was surprisingly rapid from a historical perspective. For example, from 1996 through 2001 capital inputs, which are the structures and equipment used in the production of goods and services, contributed 1.6 percentage points to the growth of potential GDP in the nonfarm business sector, compared with 0.8 percentage points during the 1991-1995 period. Potential TFP—the component of potential GDP growth that cannot be explained by increases in the amounts of capital and labor used in the economy—contributed 1.3 percentage points, up from 1.1 percentage points during the first half of the 1990s.

Because potential total factor productivity is measured as a residual to output growth—what is left when the conventional explanations have been exhausted—the determinants of its growth cannot be observed directly. But economists believe that increases in potential TFP are tied to technological progress—that is, to the application of new knowledge in the use of capital and labor.

2. See Congressional Budget Office, *CBO's Economic Forecasting Record*, CBO Paper (February 2002), p. 18.

TABLE 1-1. CONTRIBUTIONS TO POTENTIAL GROWTH IN THE NONFARM BUSINESS SECTOR, 1951-2012 (In percent)

	Average Annual Growth					
	Historical Periods					Forecast
	1951-1973	1974-1981	1982-1990	1991-1995	1996-2001	2002-2012
Potential GDP	4.0	3.6	3.2	3.0	3.9	3.4
Contributions						
Potential Hours Worked	0.9	1.5	1.1	1.1	1.0	0.9
Capital Inputs	1.1	1.3	1.1	0.8	1.6	1.3
Potential TFP	2.0	0.8	1.0	1.1	1.3	1.3
Trend TFP	2.0	0.7	1.1	1.1	1.1	1.1
TFP adjustments	0	0	0	0	0.3	0.2
Computer quality	0	0	0	0	0.2	0.1
Price measurement[a]	0	0	0	0	0.1	0.2
Security costs	0	0	0	0	0	-0.1[b]

SOURCE: Congressional Budget Office, *The Budget and Economic Outlook: Fiscal Years 2003-2012* (January 2002).

NOTE: TFP = total factor productivity.

a. In the early 1990s, the Bureau of Economic Analysis (BEA) made changes to the price indexes it uses to estimate the real output of hospital and physicians' services. Those changes created a discontinuity in the growth rates for those series, as the new price indexes showed much slower rates of increase than the old ones did. Because BEA was not able to apply those revisions retroactively, there is a slight discontinuity in measures of real (inflation-adjusted) gross domestic product and productivity between the 1996-2001 period and earlier years. In calculating potential GDP and potential TFP, CBO carries forward the effect of that new method of measuring. For example, the table shows that those changes accounted for an increase of 0.1 percentage points in the growth rate of potential TFP in the 1996-2001 period.

b. Increased security costs for private businesses in the wake of the attacks of September 11, 2001, are expected to reduce TFP growth across the 2002-2012 period; such expenditures will divert some capital and labor away from their previous uses to producing output, in the form of heightened security, that is not counted in gross domestic product.

Productivity analysts uniformly attribute a large share of the recent acceleration in TFP growth to the manufacture of computer hardware: semiconductors and computer equipment, including peripheral equipment.[3] In fact, CBO attributes all of the uptick in potential TFP growth during the latter half of the 1990s (that cannot be explained by changes in the measurement practices of the Bureau of Economic Analysis [BEA]) to technological advances in the production of computer hardware.

The growth rates of capital inputs and potential TFP are closely linked during the 1996-2001 period. Because of the very quick pace of technological progress in computer hardware production during the late 1990s, businesses and consumers enjoyed exceptionally steep declines in the quality-adjusted price of computers. For example, in the market for personal computers (PCs), the amount of computing power that a dollar could buy increased very rapidly during the latter half of the 1990s. Because TFP gains in the manufacture of computer hardware reduced the cost of business investment in that equipment, they also played a role in boosting the contribution of capital inputs to potential GDP growth.

In contrast to the unanimity about the effects of computer hardware *manufacturing*, no consensus exists yet on the degree to which computer *use* has boosted total factor productivity growth. On the basis of the performance of the U.S. economy in the late 1990s, some commentators heralded the arrival of a "new economy," in which the dissemination of information technology (IT) in the form of computer hardware, software, and communications equipment would foster rapid and widespread productivity gains. For example, those analysts posited greater innovation in the production, distribution, and exchange of goods and services made possible by linking computers within company intranets and via the Internet. By allowing more efficient use of capital and labor inputs, such computer-based innovation was expected to boost total factor productivity growth.

At least for the present, however, the contribution of a new economy to GDP growth remains a topic of debate. By increasing the amount of capital per worker (a process known as capital deepening), business investment in computers has indeed increased output per worker hour, or labor productivity. TFP growth in computer hardware *manufacturing*, by reducing the quality-adjusted price of computers, has contributed to that increase in investment in computers. Still absent, however, is compelling evidence of some portion of TFP growth that has been related specifically to computer *use* in the economy and which would reflect the fact that the application of computers in production had contributed to output and labor productivity growth

3. As categorized by the Bureau of Economic Analysis, semiconductors include microprocessors and memory chips, and computer equipment includes both traditional computers (for example, mainframes, workstations, personal computers, and laptops) and Internet servers. Other pieces of computer-related Internet equipment, however, such as routers, are classified with communications products. Peripheral equipment includes such items as printers and removable or auxiliary storage devices.

to an extent beyond what one would expect from using the same amount of any other type of capital. Similarly, the production of computer-related products such as software and telecommunications equipment has apparently not made a contribution to capital inputs or potential TFP comparable to that of computer hardware manufacturing.[4]

The recent acceleration of growth in potential TFP because of computer hardware manufacturing occurred for two reasons: the rate of technological progress in the production of those goods quickened after 1995, and the importance of computers to consumption and production in the economy grew as well. Price declines for computers, which reflected increasing quality as well as declining purchase prices, sharpened after 1995. And it is only in the past few years that the production of computer hardware has accounted for a share of overall economic output sufficient for it to make a sizable contribution to productivity growth.

A major question for the future is whether technological advances in the computer sector will continue to make an important contribution to potential TFP growth. The answer depends both on the pace of technological progress in computer hardware production and on the share of computers in total output. The faster the rate of technological progress in the manufacture of computer hardware, the more computing power potentially available to the economy. And the larger the share of computers in total output, the greater the contribution of technological advances in the computer sector to total factor productivity growth in the overall economy.

After examining the past contribution of computer hardware manufacturing to total factor productivity growth, this paper addresses that question. In particular, it answers the following:

- How is potential total factor productivity measured, and what contribution have recent advances in computer hardware manufacturing in particular made to its acceleration during the late 1990s?

---

4. The absence of measured TFP growth in the production of noncomputer IT goods may be due to the fact that official price indexes do not adequately capture the quality improvements brought about by technological advances in the production of those goods and, in particular, of communications equipment. See Congressional Budget Office, *The Need for Better Price Indices for Communications Investment*, CBO Paper (June 2001).

   One estimate finds that by attributing more quality improvements to noncomputer IT products than do official price indexes, the contribution of IT generally to total factor productivity growth would have been substantially greater during the 1990s than what was reported. However, because that increase in the first half of the decade would be roughly the same as in the second, it would not contribute to the acceleration of TFP growth in the latter period. See Dale Jorgenson and Kevin J. Stiroh, "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers on Economic Activity*, no. 1 (2000), pp. 125-236.

- What is the nature of technological progress in the computer industry, and how well is it measured?

- Is it reasonable to expect that technological progress to continue, generating potential total factor productivity gains in the future as large as those experienced in the recent past?

CHAPTER II
MEASURING POTENTIAL TOTAL FACTOR PRODUCTIVITY

In order to measure an economy's overall level of productivity, economists typically use a method known as growth accounting. That technique attributes growth in gross domestic product to increases in physical inputs, such as capital and labor, and advances or improvements in production technology. Most economic forecasters, including those of the Congressional Budget Office, apply the growth-accounting theory pioneered by Robert Solow.[1] Simple in structure, the Solow model depicts the fundamental mechanics of growth underlying the complex interactions of a modern economy.

THE BASICS OF GROWTH ACCOUNTING

The Solow model assumes that markets for physical factors of production—limited to capital and labor—and outputs are perfectly competitive and that production in the economy exhibits constant returns to scale. For example, doubling the quantity of all inputs will generate exactly twice as much output as before. Those assumptions imply that national income, or the value of all goods and services produced in the economy, is entirely distributed between capital and labor according to each factor's contribution in production.[2] Together with some additional conditions necessary for merging physical inputs and production technologies of diverse sectors, in the Solow growth-accounting framework the economy's total real output is equal to the sum of capital and labor inputs weighted by each factor's share in national income—that is, by the income share of profits (or gross returns to capital) and workers' salaries and wages, respectively.[3] To calculate each input's contribution to potential GDP, short-term or cyclical influences are excluded.

1. See Robert M. Solow, "A Contribution to the Theory of Economic Growth," *Quarterly Journal of Economics*, vol. 70 (1956), pp. 5-94.

2. To avoid double counting of primary and intermediate production, growth accounting for the economy as a whole defines output to be final sales of goods and services. A popular formulation at the industry level accounts for capital and labor as well as the use of energy, materials, and services to produce gross industry output; that formulation is known as "KLEMS" growth accounting.

3. To more precisely identify the various sources of economic growth, some approaches to growth accounting distinguish between the output growth of different sectors. For example, Jorgenson considers computer production separately from the production of other goods and distinguishes between consumption and investment within the computer sector (see Dale Jorgenson, "Presidential Address to the American Economics Association," published in the *American Economic Review*, March 2001). By identifying computer hardware's contribution to TFP growth separately from the contributions of other sectors, CBO takes a more limited, but still similar, tack.

Output that cannot be explained by the specified inputs appears as a residual in the growth-accounting equation. In analyses of potential GDP growth, economists generally identify that residual as an indicator of the contribution of inputs other than capital and labor to production and equate it with total factor productivity.[4] Often linked to technological progress, TFP may arise from improvements in production processes and management techniques. Another source of TFP gains might be research and development efforts. The capital and labor expenditures for such activity could well precede any innovative output, generating negative TFP for a time and later, after production began, positive TFP.

TFP growth is critically important to economic and budgetary outcomes. Gains in total factor productivity imply higher income and a rising material standard of living from a given quantity of capital and labor. TFP gains have a cumulative impact on economic growth because the productive skills and knowledge whose expansion TFP growth reflects do not normally depreciate over time as do, for example, additions to the stock of physical capital in the economy. Hence, even a small uptick in the rate of TFP growth can eventually have a sizable impact on the level of economic activity. For the purposes of allocating budgetary resources, higher potential TFP growth allows sacrificing fewer resources today in order to finance future commitments.

In applications of the Solow model, TFP is assumed to be "exogenous," that is, unaffected by the way capital and labor are employed in production. Identifying TFP with residual output is convenient for measurement and avoids the difficult task of modeling its causes. However, some economists question the assumption that productivity growth is best modeled as independent of other factors. Recently, economists working on growth theory have modified the Solow model to take into account the possibility that TFP growth is related to factors such as the rate of capital accumulation and, as a by-product, to transfers of knowledge among firms in the uses of that capital. In such a scenario, the overall returns to the economy from the uses of capital would exceed the private rate of return that a firm required in order to invest in equipment, although the growth-accounting model assumes a competitive rate of return in calculating the share of capital in national income. That excess of social over private returns to capital would appear as a residual in growth-accounting analyses and would increase TFP.

4. The residual may also include deviations from the model's assumptions about production, such as increasing or decreasing—rather than constant—returns to scale and noncompetitive conditions in input and output markets. The residual may also reflect errors in measuring inputs and outputs, although well-defined methods exist for both combining capital and labor inputs of different quality into lump-sum input quantities and for calculating the quantity of total output (or income) and the value of income shares. In longer-term analyses of economic growth, however, such factors are considered to be less important than is total factor productivity growth, and the residual more accurately reflects total factor productivity.

Those models are still preliminary, and to date strong empirical evidence linking TFP growth to identifiable factors has not been uncovered. Additionally, an economic forecast that eventually incorporated such factors would need to rest on a model that predicted the behavior of such factors over time in order to accurately reflect their impact on future GDP. For that reason, CBO's current practice—which consists of projecting a trend rate of total factor productivity growth that is consistent with past economic performance and that incorporates, where necessary, adjustments for newly established but likely durable influences on TFP (such as technological progress in computer hardware manufacturing)—may be more practical and no less accurate than the alternative approaches currently suggested by endogenous growth theory. Hence, along with most other forecasters, CBO continues to use the traditional Solow model for growth accounting.[5]

THE CONTRIBUTION OF COMPUTER HARDWARE MANUFACTURING TO THE ACCELERATION OF TOTAL FACTOR PRODUCTIVITY GROWTH IN THE LATE 1990s

Until very recently, economists found little evidence that computers had contributed to the growth of potential total factor productivity. In spite of the prominence of ever improving computer systems at ever lower prices, which suggests sizable TFP gains in semiconductor and computer manufacturing, the slowdown in TFP growth that began in the early 1970s continued right through the first half of the 1990s. Potential TFP in the nonfarm business sector grew at a sluggish 0.9 percent annually, on average, from 1973 to 1995, considerably more slowly than its prior post-World War II pace. During the 1996-2001 period, however, potential TFP growth rose to 1.3 percent annually. Analysts attribute much of that uptick to TFP gains in semiconductor and computer manufacturing.

Recent work by economists explains the increased role of computer hardware in economywide TFP growth during the latter half of the 1990s by pointing out, first, that technological advances in computer-related semiconductor and computer manufacturing increased after 1995. According to the Bureau of Economic Analysis, during the 1996-2000 period, prices of computers and peripheral equipment fell by 22.1 percent annually (see Table 2-1). That pace is roughly two-thirds faster than the rate of decline through the first half of the decade (-13.6 percent) and is also greater than the trend prior to 1990. Underlying that acceleration of real price decline is a combination of rapid quality increases coupled with comparatively stable or even falling purchase prices for computers throughout the late 1990s or, in

5. For a review of recent developments in growth theory, see Congressional Budget Office, *Recent Developments in the Theory of Long-Run Growth: A Critical Evaluation*, CBO Paper (October 1994); and Kevin J. Stiroh, "What Drives Productivity Growth?" *Federal Reserve Bank of New York Economic Policy Review*, vol. 7, no. 1 (March 2001).

the context of growth accounting, faster TFP growth in the manufacture of computers.[6]

A second reason that computer hardware manufacturing contributed more to TFP growth during the latter half of the 1990s is its increased share of GDP. After 1995, the annual rate of growth of business investment in computers and peripheral equipment (the largest component of final sales in the computer sector) increased to 42.6 percent, as compared with its average annual growth from 1991 to 1995 of 28.2 percent. The increases in businesses' computer purchases during the late 1990s may reflect several influences in addition to the more rapid price declines—influences that would also apply to individual consumers: preparations for Y2K, new computing opportunities offered by the Internet, and greater demand due to a growing economy. However, quality-adjusted declines in computer prices were undoubtedly an important factor.

Reflecting those increased purchases, the average annual share of final computer hardware sales in the nominal output of the nonfarm business sector rose to 1.22 percent during the 1996-2000 period, compared with its average of 1.06 percent during the 1991-1995 period and 0.98 percent from 1973 to 1995 (see Table 2-2).

In contrast to CBO's estimates of potential TFP growth during the latter half of the 1990s (presented earlier in Table 1-1), CBO's calculation of the amount of total factor productivity growth that was actually observed for the economy during that time is larger. TFP tends to rise during an economic expansion and to decline during a recession for reasons unrelated to the longer-term structural developments that estimates of potential TFP are intended to capture.[7] Because the late 1990s was a period of very strong growth, the growth rate of TFP rose by 0.6 percentage points, from 1.1 to 1.7 percent (see Table 2-3). However, according to CBO's estimate, the growth rate of potential TFP increased during that same period from 1.1 to 1.3 percent, or by only 0.2 percentage points.

---

6. The assumptions that underpin growth accounting imply that TFP growth in any sector of the economy relative to the economywide average can be measured, to a first approximation, as the difference in that sector's price trend relative to the change in the aggregate price level. Intuitively, in the case of computer hardware production, if technological advances were not present, then manufacturers of those products could not consistently improve performance while maintaining or lowering prices: the additional capital and labor inputs necessary to achieve higher quality would, in the absence of corresponding declines in the cost of capital and labor, result in price increases to cover greater production expenses. However, if capital and labor costs were decreasing for computer makers, then, in a competitive economy, they should also do so for producers of other goods. Hence, computer price declines relative to the prices of other products serve as a rough indication of the degree of TFP growth in that sector.

7. Output usually responds faster to changes in demand than do the levels of capital stock or workforce, which are less variable. Consequently, total factor productivity, or output that remains unexplained by capital and labor inputs, tends to rise during economic upswings and fall off during downturns.

TABLE 2-1. PERCENTAGE CHANGES IN THE PRICE AND QUANTITY OF PRIVATE FIXED INVESTMENT IN COMPUTERS AND PERIPHERAL HARDWARE, 1991-2000

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	1991-1995	1996-2000
Price	-10.2	-14.5	-14.7	-11.8	-16.5	-23.8	-22.6	-26.4	-23.7	-13.6	-13.6	-22.1
Quantity Purchased	8.5	35.1	26.9	23.5	50.9	44.1	45.1	43.5	41.3	39.1	28.2	42.6

SOURCE: Bureau of Economic Analysis, "Spreadsheet of Computer Purchases" (March 28, 2002), available at www.bea.doc.gov/bea/dn1.htm.

NOTE: Changes are year over year.

TABLE 2-2. NOMINAL SHARE OF COMPUTERS AND PERIPHERAL EQUIPMENT IN GROSS DOMESTIC PRODUCT, 1991-2000 (In percent)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	1991-1995	1996-2000
Nominal Share	1.08	1.06	1.01	0.99	1.15	1.21	1.24	1.17	1.13	1.33	1.06	1.22

SOURCE: Bureau of Economic Analysis, "Spreadsheet of Computer Purchases" (March 28, 2002), available at www.bea.doc.gov/bea/dn1.htm.

To compare its results with those of other economic researchers, CBO surveyed growth-accounting studies reflecting a variety of analytic approaches that differ from its own. For example, in considering the contribution of the growth in labor inputs to output growth, CBO measures hours worked and does not attempt to account for changes in the skills of the employees working those hours, although other analysts do. CBO believes that labor quality can only be crudely measured and, because it changes very gradually, has little benefit in its 10-year economic forecasts. As a result, when CBO compares computer hardware's contribution to TFP growth with the overall contribution from all other sources, changes in labor quality are treated as a residual (and appear in the "other" categories of Table 2-3). However, because other analysts have measured changes in labor quality directly, the contribution to output growth does not appear in the residual (see Table 2-3).

Another important difference among the studies stems from the method of calculating the contribution of computer hardware to TFP growth. CBO's method infers productivity growth in the computer sector by comparing price trends between computers and other output. That approach could understate TFP growth in the computer sector to the extent that computer equipment was used as an input in the production of other goods. That is, TFP growth in the computer sector, which reduced the quality-adjusted price of computers, should manifest itself in production cost savings and moderating or declining prices elsewhere in the economy. Because CBO estimates TFP growth in the computer sector on the basis of a differential rate of price decline between computers and other goods, the agency likely understates TFP growth in the computer sector and overstates it in the other sectors of the economy. In contrast, the other analysts attempt to account for the use of computers throughout the economy in order to attribute to computer hardware manufacturing that component of TFP growth in the sector that manifests itself in lower production costs in other sectors.

CBO believes that the data available for measuring the use of computers as capital inputs in individual sectors of the economy are less reliable than data on the amount of computer capital in the economy overall and that making assumptions about such sector-specific computer use in the future in order to project TFP growth in the sector would result in inaccurate economic forecasts. Consequently, in its estimates of total factor productivity in the computer sector, CBO does not attempt to account for computer-based cost savings in other sectors of the economy.

In spite of such differences, however, one result emerges clearly from all of the analyses: the production of computer hardware has accounted for a major share of the acceleration in TFP growth during the latter half of the 1990s.[8]

---

8. TFP gains and capital deepening completely determine the rate of labor productivity growth, or the growth in output per hour worked. CBO estimates that actual (as opposed to potential) labor productivity growth rose from an annual average of roughly 1.6 percent during the 1990-1995 period to 2.7 percent

TABLE 2-3. THE COMPUTER HARDWARE SECTOR'S AND OTHER SECTORS' CONTRIBUTIONS TO THE RECENT ACCELERATION OF TOTAL FACTOR PRODUCTIVITY GROWTH

Author of Study	Time Periods Compared	Increase in the Average Annual Rate of TFP Growth (In percentage points)	Contributions (In percentage points)		Share of TFP Growth (In Percent)	
			Computer Hardware	Other[a]	Computer Hardware	Other[a]
Congressional Budget Office	1996-2000 and 1991-1995	0.60	0.16	0.45	27	73
Jorgenson et al.[b]	1995-2000 and 1973-1995	0.51	0.27[c]	0.24	53	47
Oliner and Sichel	1996-2000 and 1991-1995	0.50	0.30	0.20	60	40

SOURCES: Congressional Budget Office; Dale W. Jorgenson, Mun S. Ho, and Kevin J. Stiroh, "Projecting Productivity Growth: Lessons From the U.S. Growth Resurgence" (December 11, 2001), available at www.frbatlanta.org/frbatlanta/filelegacydocs/stiroh.pdf; Stephen D. Oliner and Daniel E. Sichel, "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" Federal Reserve Board (February 2000; updated results, November 27, 2001), available at www.frbsf.org/economics/conferences/000303/papers/resurgerce.pdf.

a. Includes contributions from sectors other than computer hardware manufacturing, as well as influences of business cycles and the impact of changes in the mid-1990s that U.S. statistical agencies made in the way they measured prices.

b. Results based on private GDP, which includes both farm and nonfarm output.

c. Includes software and communications equipment.

THE ACCURACY OF GROWTH-ACCOUNTING RESULTS AMID ECONOMIC AND TECHNOLOGICAL CHANGE

The consensus of growth accountants is that much of the recent acceleration in total factor productivity growth during the latter half of the 1990s can be explained by the contribution of technical advances in semiconductor and computer manufacturing. Several qualifications to the analyses are worth mentioning, but they do not seriously weaken that conclusion.

during the 1996-2000 period, with much of that acceleration due to TFP gains in the computer hardware sector and to capital deepening related to computers (0.16 and 0.47 percentage points, respectively).

First, estimates of TFP growth (either potential or actual) are subject to change both from revisions to data and from the economy's subsequent performance. In essence, because little time has elapsed since the end of the 1990s, evidence on the magnitude of TFP gains during the latter half of that decade as well as the durability of those gains is still emerging. Depending upon the data and analytic approach used, even contemporaneous estimates of potential TFP growth can vary. CBO's current estimate of potential TFP growth of 1.3 percent annually during the 1996-2001 period is somewhat lower than the Council of Economic Advisers' estimate of 1.4 percent for the 1995-2001 period, but both are well within the range of estimates by other forecasters.[9]

Additionally, short-term deviations from the assumptions of the growth-accounting model that have nothing to do with technological change may be interpreted improperly as a longer-term acceleration in potential TFP growth. For example, greater competition in computer manufacturing would show up as TFP gains in the economy because it would reflect a more efficient use of the economy's resources: increased competition would bring computer prices closer to the actual cost to manufacture those products.

Measurement issues are also a source of potential qualifications to estimates of total factor productivity. Because technological advances can alter the nature of both production processes and the goods and services produced, their impact can be difficult to measure. In particular, controversy has arisen about a statistical method called "hedonic" price measurement, which U.S. statistical agencies such as the Bureau of Labor Statistics (BLS) use to infer price declines for computers that result from improvements in quality.[10]

New models of computers typically offer faster processor chips, more memory, and generally more capabilities than earlier vintages. However, thanks to technological advances, the purchase price for a new computer often will be similar to that of older models with fewer attributes. In such cases, a simple price comparison between the old and new models will not reflect the decline in the price of computing that has taken place. Because consumers pay roughly the same amount as before but receive greater performance from the new computer, if quality is held constant the price of computing has actually fallen.

---

9. For a comparison of sharply different estimates of potential TFP growth see Robert Gordon, "Discussion of Martin N. Baily and Robert Z. Lawrence: 'Do We Have a New E-conomy?'" (paper presented at the American Economic Association annual meeting, New Orleans, La., January 5, 2001), available at http://faculty-web.at.northwestern.edu/economics/gordon/B&LNewEcon.pdf. The Council of Economic Advisers' estimate of structural TFP growth is found in the *Economic Report of the President* (Washington, D.C.: U.S. Government Printing Office, 2002).

10. The Bureau of Labor Statistics supplies almost all of the price indexes that the Bureau of Economic Analysis uses to calculate real GDP.

The usefulness of hedonic price techniques (whose application is not limited to computers) is that they allow for a valuation of products' additional features so that price comparisons between two computers of different vintages can reflect quality-adjusted price changes. Because the growth in real computer production—and one may interpret this quantity as the number of units capable of producing a given amount of computing power—is obtained by dividing the index of nominal computer output by the computer price index, a more rapid decline in computer prices implies faster growth in the amount of computing power produced.

Some commentators claim that hedonic measurement overstates the decline in computer prices due to quality improvements. By that view, official U.S. statistics would overstate real computer production and, with it, output growth and productivity in the economy. Additionally, because many other countries do not apply hedonic techniques in their price indexes, comparisons of productivity growth between the United States and other countries could be distorted.[11]

Recent work by economists at the Federal Reserve and the Organization for Economic Cooperation and Development (OECD) has addressed those concerns. The study by the Federal Reserve shows that a hedonic price index for semiconductors and computers displays almost exactly the same trends as a more standard "matched-model" price index, in which prices of representative computer models are tracked from market introduction to discontinuance.[12] The OECD study finds that, in countries where official statistical agencies do not apply hedonic price techniques, adjusting real computer output for quality improvements produces only modest effects on measured overall economic growth. In such countries, because net imports are subtracted from domestic production in tallying final sales of goods and services, increases in domestic computer output are often reduced by increases in the real value of computer imports, which tends to be relatively high.[13]

---

11. For a review of such critiques see Gene Epstein, "Why the 'Hedonics' Debate Is a Lot of Baloney," *Barron's*, September 11, 2000. See Appendix A for more on hedonic price estimation.

12. Ana Aizcorbe, Carol Corrado, and Mark Doms, "Constructing Price and Quantity Indexes for High Technology Goods," (paper presented at the National Bureau of Economic Research workshop on Price Measurement, Cambridge, Mass., July 26, 2000). The matched-model price index differs somewhat in the data it relies on and in its construction from its counterparts calculated by the Bureau of Labor Statistics. In particular, for the matched-model index the computer price data are proprietary and allow for frequent observations of computer prices and sales. As a consequence, in each period the index can reflect updates to both the price comparison for all models and the weight each individual price comparison receives in the calculation of the index. BLS prefers to get price quotes directly from producers (for the producer price index) and retail outlets (for the consumer price index)—data that do not allow for such frequent updating.

13. See Paul Schreyer, "Computer Price Indices and International Growth and Productivity Comparisons," OECD Statistics Directorate (April 2001), available from Paul.Schreyer@oecd.org.

Finally, an emphasis on the role that technological advances in computer-related semiconductors play in TFP growth misses a potentially important contribution that other types of semiconductors in products other than computers make. Estimates for many of those goods—for example, machine tools—do not incorporate the hedonic adjustments for quality changes that the estimates for computers enjoy. By different tallies, estimates of semiconductor shipments for noncomputer products have accounted for from 49.6 percent of worldwide sales (according to a 1998 figure by the World Semiconductor Trade Statistics [WSTS] organization) to 70 percent (according to a 1999 figure by the Semiconductor Industry Association).[14]

14. The WSTS breaks out noncomputer semiconductor shipments as follows: communications products, 18.8 percent; consumer electronics, 14.9 percent; industrial equipment, 8.9 percent; automobiles, 5.8 percent; and military goods, 1.1 percent. BLS currently incorporates hedonic methods in the consumer price indexes for microwave ovens, refrigerators, VCRs, DVD players, camcorders, consumer audio products, and televisions.

CHAPTER III
PRICES OF COMPUTERS AND COMPONENTS

The finding from the growth-accounting studies that information technology has been an engine of productivity growth over the past five years says little about why the quality-adjusted prices of computers have fallen so steeply during that period. Industry analysts have over the years made two observations about computer prices: first, that component prices largely follow a predictable pattern of decline, and second, that computer price declines largely reflect declines in the prices of components. For decades, computer component prices have fluctuated around a path that has declined steadily.

Despite the commonplace observation of industry analysts that the decreases in component prices account for most of the decreases in computer prices, federal statistics are not collected or compiled in such a way as to make that assertion easy to put into a growth-accounting framework. Without such data, economists cannot accurately assess the relative contributions of the different factors behind the computer price decline. Instead, economists present various scenarios and attach some degree of plausibility to each one.

THE TECHNOLOGY TRAJECTORY AND MARKET SWINGS

In the computer and components industries, two sets of factors—technological and market—interact to set the direction and level of prices. In the short term, conditions on both the supply and demand sides of the market (for example, the amount of production capacity and demand for a particular integrated circuit) cause prices to fluctuate around the underlying downward trend. Over the longer run, however, the technology trajectory, as it has been termed, sets the underlying direction of prices—which has been decidedly downward for the past 30 years.

For computer systems, a pattern of improvement through new technologies for components has repeated itself over the past several decades. Engineers provide new generations of integrated circuits with more transistors and capabilities, the information-holding capacity of computer disk drives rises, and the capabilities of computer systems thereby increase. Then, through competition, prices fall.

Among producers of integrated circuits, that predictable pattern of improvement has been enshrined in the observation known as Moore's Law, which states that the number of transistors on leading-edge integrated circuits will double every

18 months.[1] That observation, which generally has held for over 35 years, has important implications for price and performance. Semiconductor manufacturers are able to put ever more transistors on the integrated circuits mainly by shrinking the size of the individual transistors and the wires connecting them.[2] Smaller transistors are faster than bigger ones and can be cheaper to produce. Thus, Moore's observation about the number of transistors implies that, generally, integrated circuits will decline perennially in price while increasing in capacity and speed. (The prevalence of Moore's Law also drives competition in the semiconductor industry. Companies generally expect it to play out and fear that their competitors may benefit from it. Consequently, semiconductor producers build into their research and development and investment plans that expectation of regular improvement.)

The interaction between the technology trajectory and the market swings reveals itself clearly in the price of computer memory circuits. In some periods, such as the late 1990s, prices for dynamic random access memory (or DRAM, the main type of memory chip used in computers) have declined rapidly (see Figure 3-1). In other periods, such as in the early 1990s, prices were stable. And, on at least one occasion, prices rose—following the 1987 Semiconductor Trade Accord between the United States and Japan. Overall, over the past 22 years, prices per unit of memory have declined by an average of 32 percent per year.[3] By comparison, the price of electricity fell by only 5.5 percent per year in the decades after its introduction.[4]

In the period after 1995, in particular, DRAM prices fell quite rapidly, much more rapidly, in fact, than the long-term trend. Because the amount of memory is one of the principal factors that federal agencies use in their quality adjustments of computer prices for statistical purposes, the dramatic drop in memory prices over several years has contributed substantially to the drop in quality-adjusted computer prices.

---

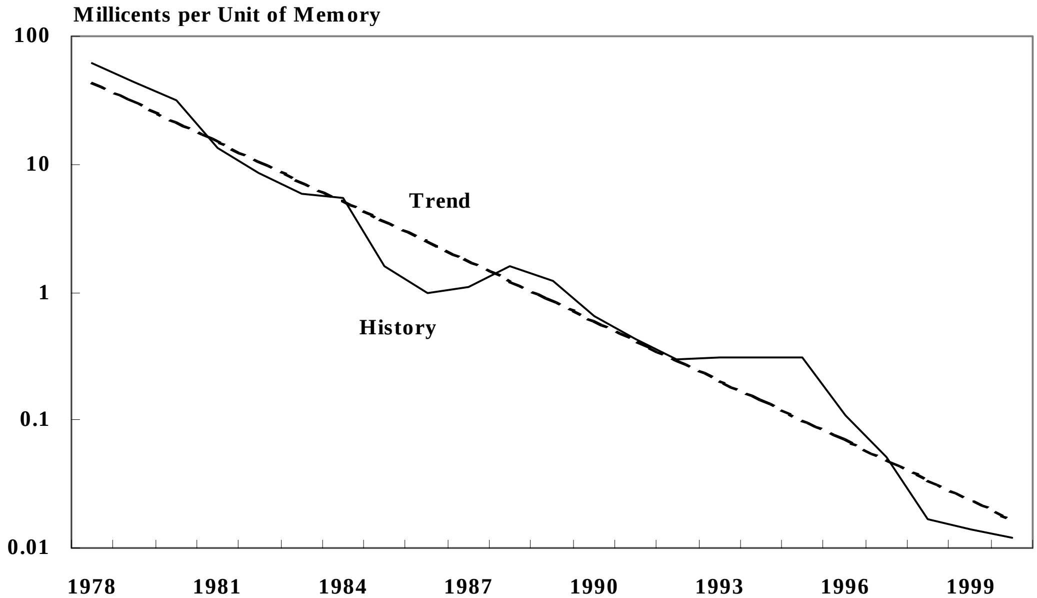
1. Originally, Gordon Moore foresaw a doubling every year. But after a few years, he altered that time span to every 18 months. For an extended discussion of the economic import of Moore's Law, see Kenneth Flamm, "Moore's Law and the Economics of Semiconductor Price Trends" (paper presented to the National Research Council Symposium on Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions, Kennedy School of Government, Harvard University, Cambridge, Mass., September 24, 2001; updated draft, December 2001).

2. They have increased the size of integrated circuits as well, but that change is secondary.

3. Kenneth Flamm calculates a 37 percent annual price decline for the 1971-1995 time period. Obviously, rates of decline are sensitive to the time period chosen. See Kenneth Flamm, *More for Less: The Economic Impact of Semiconductors* (San Jose, Calif.: Semiconductor Industry Association, December 1997), p. 6.

4. William Nordhaus, "Progress in Computing" (paper presented at the Workshop on Economic Measurement: Hedonic Price Indexes: Too Fast? Too Slow? Or Just Right?, The Brookings Institution, Washington, D.C., February 1, 2002), available at www.econ.yale.edu/~nordhaus/homepage/recent_stuff.html.

FIGURE 3-1. PRICES FOR DYNAMIC RANDOM ACCESS MEMORY, 1978-2000



SOURCE: Congressional Budget Office based on data from Micron Technologies and other industry sources.

NOTE: The figure uses a logarithmic scale in the price axis. The prices at the beginning of the period are so much higher than those at the end—by close to five orders of magnitude—that presenting the same information using an arithmetic scale would obscure most of the interesting phenomena after 1987.

Economists trying to understand the industry confront a difficult problem in separating out the influence of technological factors and market factors in memory prices and other computer and component prices.[5] Although both sets of factors may have influence, federal statistical agencies do not distinguish between them in their analyses of the prices of computers and their components. Instead, those agencies are charged with measuring prices and quantities and changes in them; determining why the prices and quantities change is outside their responsibility.

For example, the Asian currency crisis of the late 1990s—a market factor—probably contributed to the very rapid decline in memory prices. PC makers responded to that decline by increasing the amount of memory bundled in each machine they sold. Federal statistical agencies, when they applied their quality-adjusting techniques to PC prices, recognized that each PC had more memory and determined how much that increased the value of each machine. They did not then distribute that change in value among the various causal factors.

5. The computer industry is not unique in this regard. In any industry undergoing rapid technological changes simultaneously with changes in market conditions—for example, the pharmaceutical industry—ascribing price changes to one factor or another is difficult.

Separating out technological and market factors in the late 1990s is the subject of much of the next chapter. The central point is that in these industries, technological advances are the principal source of continuing declines in quality-adjusted prices, while market factors tend to vary.

THE IMPACT OF DECREASES IN COMPONENT PRICES ON COMPUTER PRICES IN THE LATE 1990s

Casual observation suggests that declines in the quality-adjusted (and, in many instances, nominal) prices of the principal components of personal computers (most notably, semiconductors and computer storage devices) largely explain the long decline in the prices of computers, including the 70 percent fall in the late 1990s.[6] Yet trying to estimate how much semiconductors and storage devices contributed to computer systems' price decline by employing the data recorded in the Census Bureau's Census of Manufacturers produces an implausibly low estimate. That calculation, which weights the components' price declines by their share of total manufacturing costs, finds that price declines in those two components (semiconductors and storage devices) explain only about 17 percentage points of the 70 percent decline in quality-adjusted prices of systems (see Table 3-1). Using other estimates of those components' share can raise their contribution substantially, up to 47 percentage points. Nevertheless, much of the price decrease remains unaccounted for by this method.

The official Census Bureau data are implausible on two fronts. First, the bureau's figures suggest that semiconductors of all types (including microprocessors, memory chips, and integrated circuits, as well as individual transistors and diodes) account for only 14 percent of the value of computer shipments. Second, those same figures also imply that the value of computer storage of all types (hard drives, floppy drives, CD drives, and tape backups) account for only 4 percent of the value of the computer shipments. For a number of reasons, CBO and other researchers believe that the official weights are inaccurate, and in its

6. That estimate excludes computer services, which have not experienced the same technological advances as computer hardware. To derive the estimate, CBO used the Bureau of Labor Statistics' producer price index for primary products of the electronic computer industry, which excludes the computer services component. In contrast, the producer price index for the computer industry normally includes such services.

TABLE 3-1. PRICE DECLINES FOR COMPUTER COMPONENTS COMPARED WITH THOSE FOR COMPLETE COMPUTER SYSTEMS, 1995-2000 (In percent)

	Share of Value of Shipments	Cumulative Price Change, 1995-2000	Contribution to Price Change for Complete Systems
Estimate Based on Federal Statistics			
Semiconductors	14	-98[a]	-14
Computer Storage Devices	4	-67	-3
Total	18		-17
Middle Alternative Estimate			
Semiconductors	30	-98[a]	-29
Computer Storage Devices	5	-67	-3
Total	34		-32
High Alternative Estimate			
Semiconductors	45	-98[a]	-44
Computer Storage Devices	5	-67	-3
Total	50		-47
Memorandum:			
Complete Computer Systems	100	-70	-70

SOURCES: Congressional Budget Office based on the following: in the estimate based on federal statistics, the shares of the value of shipments are from Department of Commerce, Bureau of the Census, *1997 Economic Census, Manufacturing, Industry Series, Electronic Computer Manufacturing* (August 1999), p. 11. In the alternative estimates, semiconductors' shares are based on Jack E. Triplett, "High-Tech Industry Productivity and Hedonic Price Indexes" (paper presented at the Workshop on Industry Productivity: International Comparison and Measurement Issues, The Organization for Economic Cooperation and Development, May 2 and 3, 1996), p. 136. In all of the estimates, cumulative price changes for semiconductors are based on Ana Aizcorbe, Kenneth Flamm, and Anjum Kurhid, "Price Indexes for Semiconductor Inputs to the Computer and Communications Industries" (paper presented at the Workshop on Communications Output and Productivity, The Brookings Institution, Washington, D.C., February 23, 2001); those price changes for computer storage devices are from the index of import prices by the Bureau of Labor Statistics (BLS). The price change for complete computer systems is from BLS's producer price index for primary products in the computer industry.

a. Semiconductor price changes are weighted by consumption by computer manufacturers.

alternative estimates CBO has attempted to adjust each weight to remedy those deficiencies.[7]

With regard to semiconductors, the share estimate based on the Census Bureau's data includes only those purchased semiconductors that are reported as specific components. However, for 1997, Census reports $17 billion (or over 40 percent) of the $40 billion spent on inputs purchased by computer system manufacturers as "miscellaneous" or "not separated by kind." Researchers who have looked more closely at the industry have concluded that a large part of that 17 billion dollars' worth of purchased inputs are, in fact, either semiconductors or disk drives. For its alternative estimates, following an analyst at the Brookings Institution, CBO assumed that during the 1995-2000 period, purchased semiconductors (and semiconductors that computer makers manufactured for their own internal use) accounted for 30 or 45 percent of the value of systems.[8]

With regard to computer storage, IBM and some other computer manufacturers make computer storage devices for their internal use. Those internally used components exhibit the same quality improvements as purchased ones and serve to reduce the cost of computer systems. However, the official estimates do not include such internally used components.[9] According to one reputable industry source, in the late 1990s internal use represented about a quarter of all disk drive sales.[10] CBO therefore adjusted the share of computer storage up from 4 percent of shipment values to 5 percent.

Despite those adjustments, CBO's alternative estimates may still understate the contribution of improvements in semiconductors and computer storage devices to the overall quality of computers. Quality improvements in components often permit savings of labor and other nonmaterial costs, but those savings are not

7. In addition to correcting for errors in shares, CBO also used price deflators appropriate to the calculations. Rather than use the Census Bureau's price indexes for all semiconductors, CBO adopted an index weighted for semiconductors used in computers, which was developed by Aizcorbe and others. See Ana Aizcorbe, Kenneth Flamm, and Anjum Kurhid, "Price Indexes for Semiconductor Inputs to the Computer and Communications Equipment Industries" (paper presented at the Workshop on Communications Output and Productivity, The Brookings Institution, Washington, D.C., February 23, 2001). Rather than use BLS's producer price index, which captures only domestically manufactured computer storage devices (which are largely niche or specialty products whose price patterns do not reflect prevailing trends), CBO relied on BLS's index of import prices.

8. Jack E. Triplett, "High-Tech Industry Productivity and Hedonic Price Indexes" (paper presented at the Workshop on Industry Productivity: International Comparison and Measurement Issues, The Organization for Economic Cooperation and Development, May 2 and 3, 1996), p. 136, available at www1.oecd.org/distilsti/stat-ance/prod/measurement.htm.

9. The Census Bureau's estimates may include purchased components used to manufacture disk drives used internally but would not indicate that those components were part of the computer storage devices.

10. See www.disktrend.com/newsrig.htm.

recognized in the estimates. For example, if more-sophisticated microprocessors mean that there are fewer assembly steps—because microprocessors now integrate more functions—the resulting improvement in labor costs will not be attributed to improvement in the components, even though that savings traces back to the components. Similarly, the cost accounting method would not reflect advances in the principal components that permit savings in other material costs—because of, say, the ability to use fewer or smaller printed circuit boards to perform the same function.

CBO's alternative estimates also do not include the contribution of components other than semiconductors and computer storage devices because the price declines in other components have not been published. Computer monitors, for example, have improved consistently over the past decade, increasing in size and performance while coming down in price. However, CBO was unable to find systematic data on quality-adjusted prices for computer monitors and so could not include them in its calculations. A similar situation holds for printed circuit boards, but again systematic data were difficult to come by.

In sum, even after adjusting for the obvious errors and omissions in the official data, between a third and a half of the decrease in quality-adjusted prices for computer systems remains unexplained by decreases in quality-adjusted prices of semiconductors and computer storage devices.[11] An unknown share of the rest may be explained by decreases in the quality-adjusted prices of other components, like computer monitors and printed circuit boards. Finally, some part of the residual can be assigned to improvements in the manufacture of computer systems themselves.

TRENDS IN THE MANUFACTURE OF COMPUTER SYSTEMS

Technological advances in the manufacture of computers usually get less notice than the improvements in components. But advances in the way computers are assembled have contributed to the cost reductions enjoyed by computer buyers. Even if the assumptions underlying CBO's high alternative estimate of the contribution of semiconductors and computer storage hold true, a large fraction of the total decrease in computer prices remains unexplained (see Table 3-1). Improvements in other components undoubtedly account for some of that unexplained residual, but the efforts of computer manufacturers also contributed to the decline.

11. See McKinsey Global Institute, *U.S. Productivity Growth, 1995-2000: Understanding the Contribution of Information Technology Relative to Other Factors* (Washington, D.C.: October 2001). The McKinsey Global Institute also estimates that over half of the decline in computer system prices can be explained by declines in component prices.

The manufacture of computers exhibits some clear trends. The market share of the most efficient manufacturers is rising. Furthermore, the different segments of the computer market continue to grow more alike technologically. The PC segment of the market and the more technical parts of the midsized computer market overlap to some degree. Still, the brutal competition of the PC market has not come to all parts of market for midsized computers.

Personal Computers

Independently of the drop in component prices, manufacturers are increasingly assembling personal computers in new ways. In the past few years, computer manufacturing has been becoming more efficient principally through two different trends: build-to-order and contract manufacturing. Those methods still account for less than half of computer production, but industry observers expect their market shares to grow. However, that shift in the price structure of the industry is a one-time event, rather than a continuing source of price decreases, although it may be so stretched out over time as to seem a continuing source of productivity growth.

Build to Order. In response to the high rate of obsolescence, with new models introduced every few months, some computer manufacturers strive to systematically reduce their inventory costs. At the extreme, some makers build a computer only after they receive an order for it. In addition to reducing inventory expenses, that strategy allows customers a great deal of latitude in customizing their machines. One of the larger personal computer makers, Dell Computer Corporation, has executed the strategy with exceptional success.

To execute the strategy successfully, Dell has had to coordinate its different operations very closely.[12] Competitors who have tried to follow have often not had the same level of success. Dell's market niche—businesses and sophisticated consumers—may favor its strategy.

Contract Manufacturing. Personal computer makers have begun to contract out the actual production to third parties that specialize in low-cost manufacturing, leaving the original companies to specialize in other functions in which they may have a comparative advantage: design, building a brand name, distribution, and service.[13] According to industry observers, contract manufacturers have been growing faster

12. Kenneth Kraemer, Jason Dedrick, and Sandr Yamashiro, *Refining and Extending the Business Model with Information Technology: Dell Computer Corporation,* Center for Research on Information Technology and Organization, University of California at Irvine, Irvine, Calif. (May 19, 1999), available at www.crito.uci.edu/.

13. Stephen Shankland, "Who Really Makes PCs?" *CNET News*, February 9, 1999, available at http://news.cnet.com/category/0-1003-202-338486.html.

than the electronics industry as a whole and consequently account for a larger fraction of annual sales. Their share of the market is greater for the less expensive consumer-oriented personal computers than for the more expensive PCs aimed at businesses and professionals. However, those lower-end machines have put substantial pressure on the whole pricing structure.

Contract manufacturers often work for more than one PC company and work in multiple countries to benefit from low wages. To the extent that PCs share the same components, that approach may give contract manufacturers economies of scale in purchasing and handling components. The contract manufacturers also typically have lower overhead costs than do the major brand-name PC manufacturers.

Contract manufacturing allows the brand-name manufacturers to compete with the generic PC manufacturers, who constitute about a quarter of the U.S. market and a larger fraction abroad. The low-cost extensions of their product line have allowed the brand-name manufacturers to capture a larger share of the total market, and industry observers estimate that contract manufacturers' share of industry revenues will double over the next few years.[14]

Mainframe and Midsized Computers

The rise of the Internet has created a renaissance in the markets for mainframe and midsized computers. Some companies use those types of computers as the heart of their Internet presence as electronic commerce servers or the like. Such applications have put mainframe and midsized computers in direct competition with computer workstations for that Internet business, so the product lines have become more dynamic technologically and more competitively priced.

The appearance of Intel and Advanced Micro Devices (AMD) in the market for microprocessors designed for midsized computers has the potential to alter that market.[15] While the microprocessors currently powering most personal computers process information 32 bits at a time, Intel has been working on a microprocessor—the Itanium—that operates on 64 bits at a time. AMD has responded with the announcement of a microprocessor—the so-called Hammer—that works along similar lines, but rather than being a single 64-bit microprocessor, it bundles twin 32-bit computational engines in a single integrated circuit. Both Intel's and AMD's

14. Shankland, "Who Really Makes PCs?"

15. See John Spooner, "Intel to Showcase Networking, Servers," *CNET News*, February 13, 2002, available at http://news.com.com/2100-1001-837084.html. See also Michael Kanellos, "AMD Wields Its Hammer" *CNET News*, February 26, 2002, available at http://news.com.com/2100-1001-845621.html.

microprocessors are intended to allow those companies to compete in the market for microprocessors for high-end Internet servers, now dominated by Sun Microsystems, IBM, and Hewlett-Packard. Computer systems based on the first generation of those microprocessors are currently available, and second generation systems will become available later in 2002.

At present, however, competition is not as strenuous in the market for mid-sized computers as it is in the PC market. Consequently, in the long run the price declines in the former market are unlikely to match those in the latter market. Furthermore, companies that buy high-end servers typically have established fleets of them running mission-critical applications; that established base may delay or limit acceptance of the new processors.

CHAPTER IV
THE TECHNOLOGICAL OUTLOOK AND ITS IMPLICATIONS FOR THE NEXT DECADE

The performance of the U.S. economy in the late 1990s owes much of its vitality to an increase in the rate of productivity growth compared to what it was during the 1970-1995 period. Growth accountants have identified the computer industry as a major source of that increase, owing to technological improvements and prices that declined more rapidly than before. The willingness of consumers and businesses to buy more computing power increased the share of real gross domestic product accounted for by computers. That greater weight given to computers in the national income and product accounts amplified the effect of those technological improvements on economywide productivity measures.

Will the quality-adjusted prices of computer systems and their components continue to fall at the rapid pace of the late 1990s, or will they revert toward the longer-term trend? CBO believes that the underlying rate of technological improvements in computers and their components will continue at the accelerated rate of 1996 through 2000 but that the end of certain transitory factors that also forced prices down will leave the overall rate of decline in computer system prices less rapid than what was recorded for that period but still above the longer historical trend of 1970 through 1995. Those technological advances will continue, however, only if forces both on the supply side and the demand side of the market continue along their existing paths. This chapter examines future trends for some of the more important computer components as well as in the demand side of the market.

TECHNOLOGICAL TRENDS FOR INTEGRATED CIRCUITS

Industry experts are fairly optimistic that at least for the next five to seven years, the pace of technological improvements in integrated circuits will be no slower than the technology trajectory of the last 30 years.[1] If so, integrated circuit manufacturers will introduce a new generation of memory chip that is four times as capable as its predecessor every three years. Those same experts disagree, however, about whether the pace of the late 1990s (when a new generation of chip was introduced every two years) will hold in the future. No single issue defines the conflicting points of view; rather, where a particular expert stands depends on judgments about how fast the industry will put into place a number of improvements in the production process that are necessary to manufacture more-capable chips. Currently, the more fundamental issues concerning the absolute limits of the silicon-based

1. Semiconductor Industry Association et al., *International Technology Roadmap for Semiconductors, 2001 Edition* (San Jose, Calif.), available at http://public.itrs.net/Files/2001ITRS/Home.htm.

integrated circuit and the costs that would be incurred in moving to radically different circuitry and manufacturing processes are not believed to be imminent.

Two types of integrated circuits are especially important to the 10-year outlook for computers: microprocessors that manipulate data either logically or numerically, which have defined the evolution of personal computer models (the Pentium family, for example) and memory circuits that store the data for short periods of time. At present, microprocessors and DRAMs pose the greatest challenges to the ability of producers to continue their aggressive rate of advances. Typically, other chips will use the newly developed technology after it is perfected on the leading production lines.

In addition, two other types of integrated circuits play an important role in the development of computers: digital signal processors, which control the signals between a computer's processor and its peripherals, such as the monitor and speakers and modem, and application-specific integrated circuits (ASICs), which (as their name implies) are chips intended to serve particular purposes, most notably in the past several years the operation of communications devices. Digital signal processors and ASICs face many similar design and production constraints as microprocessors do, so many of the upcoming comments about microprocessors apply to them as well. However, the market conditions for microprocessors and digital signal processors and ASICs differ significantly.

Microprocessors

Recent analyses of the microprocessor market suggest that the current market leaders will be able to continue the rapid pace of technological change for the next several years.[2] Intel, the leading microprocessor maker, has announced that it has developed new transistor technology that will allow it to double the clock speed of its leading-edge microprocessors every two years at least through 2007.[3] That pace of improvement is the same as that during the 1995-1999 period.

---

2. John Markoff, "The Increase in Chip Speed Is Accelerating, Not Slowing, *New York Times*, February 4, 2002, available at www.nytimes.com/2002/02/04/technology/04CHIP.html.

3. Gerald Marcyk, "Breaking Barriers to Moore's Law" (paper presented at the Intel Developer Forum, February 28, 2002), p. 6, available at www.intel.com/research/MarcykIDF022802.pdf.

   The clock speed (or rate) of a microprocessor simply measures the speed at which the microprocessor performs its basic operations. That rate does not measure the amount of useful work a microprocessor can do, so computer professionals have developed a series of benchmarks to do that. However, because computer buyers have come to use microprocessor speed as a rough gauge of the capabilities of a computer and the value of their purchase, economists generally use microprocessor speed as an input for most models of quality adjustment for computers. Moore's Law applies to the transistor count, not to the clock speed, although Intel's announcement also refers to Moore's Law.

In a similar vein, a recent analysis by the McKinsey Global Institute is optimistic about the ability of microprocessor producers to keep their productivity growing at or near the levels of the late 1990s.[4] McKinsey analysts believe that increased competition in the microprocessor market drove Intel and AMD to continuously modernize their product lines—and to do so much more rapidly than they would have otherwise. That accelerated modernization did not affect just the most sophisticated microprocessors: it caused the entire market for microprocessors to become more dynamic technologically. Essentially, fear of falling behind forced both companies to increase the frequency with which they introduced new microprocessors into all segments of the computer market. On the basis of its industry contacts, McKinsey concludes that although the microprocessor market will keep up its rapid rate of technological change for the next few years, the unit sales of computers and microprocessors will decline, which should reduce the rate of the sector's productivity growth slightly.

The major risk to this optimism in the microprocessor market is that competition between AMD and Intel might lessen, either because AMD would falter technologically or financially or because the dynamics of the duopoly would change. Should either occur, Intel might feel much less pressure and might return to the pattern of price reductions of the early 1990s, when it enjoyed less competition. At this point, however, AMD still provides strong competition to Intel and actually increased its market share in 2001.[5]

Memory Circuits

In an effort to continue its record of progress, the worldwide semiconductor industry has constructed a process to identify the likely technological challenges it faces. The resulting *International Technology Roadmap for Semiconductors*, as it is called, is not a forecast but a consensus analysis of the performance requirements for semiconductor manufacturing technology that must be met or worked around if overall progress is to continue.[6] (See Box 4-1 for a list of the technological challenges to rapidly improving the manufacture of integrated circuits.) The severity and number of the performance requirements led the analysts who developed

4. McKinsey Global Institute, "Semiconductor," *Productivity in the United States, 1995-2000: Understanding the Contribution of Information Technology Relative to Other Factors* (October 2001), available at www.mckinsey.com/knowledge/mgi/reports/Productivity.asp.

5. John G. Spooner, "AMD Scores Points Against Intel in 2001," *CNET News*, January 24, 2002, available at http://news.com.com/2100-1001-822642.html.

6. Semiconductor Industry Association et al., *International Technology Roadmap*.

BOX 4-1.
TECHNOLOGICAL CHALLENGES IN FABRICATING INTEGRATED CIRCUITS

Fabricating a state-of-the-art integrated circuit requires many different processes and steps. The precision to accomplish most of those steps successfully has become quite demanding over the years. In each instance, the challenges come from a common problem: fitting a rapidly increasing number of transistors into a constant (or only slightly increasing) area. Maintaining the improvements will require balancing two factors: stringency and cost. Some new processes will meet the technical criterion of fabricating minuscule transistors but will be slow and, consequently, costly. Current processes, in contrast, may be less costly but have reached their technical limits. Below are some of the major aspects of fabrication and the challenges faced in them:

Design: Leading-edge integrated circuits currently have component transistors numbering in the hundreds of millions (and soon in the billions). Design becomes even more difficult as the transistor count rises.

Materials: As transistors shrink, the electronic characteristics of commonly used materials may become insufficient to the task. Some existing materials used in integrated circuits may be hitting the limits of their scaling. But switching materials while maintaining a rapid pace of technological advance may be a challenge. Furthermore, as scales shrink, fabrication processes become less forgiving.

Lithography allows the maker to define areas in the semiconductor material for chemical and electronic transformation. Manufacturers are now working in scales shorter than the wavelength of light, which will have to shrink to even shorter dimensions.

Interconnection, that is, wiring hundreds of millions (and soon billions) of transistors together in an area the size of a postage stamp, will require new materials and a new level of control and precision.

Assembly and Packaging: Some of the microprocessors will have packages with 800 wires that connect to the rest of computer. Connecting all of the wires to each integrated circuit in a cost-effective manner will require innovation in assembly and packaging.

Testing such integrated circuits with more and more transistors rapidly and cost-effectively will require redesigning test equipment.

SOURCE: Semiconductor Industry Association et al., *International Technology Roadmap for Semiconductors, 2001 Edition* (San Jose, Calif.), available at http://public.itrs.net/Files/2001ITRS/Home.htm.

the *Roadmap* to suggest that after 2001, the rate of technological progress may revert to the historical norm of a new generation of DRAM technology every three years, whereas between 1995 and 2000, a new generation of DRAM technology was introduced every two years.[7]

However, the *Roadmap* has been criticized as being too conservative in its assessment of the industry's ability to overcome technological challenges. In recent years, semiconductor technology has improved more quickly than the *Roadmap* has implied, a trend that will continue if Intel's forecast proves to be accurate.

No single actor plays a determining role in the largest memory chip market: the DRAM market. In the absence of unforeseen changes in the market structure, competitive pressures will force the major makers of DRAMs to offer new products as rapidly as they become technically feasible.

Transitory Factors

Some analysts believe that a confluence of transitory and one-time phenomena that are unlikely to be repeated explains a large part of the boost in technical innovation of the late 1990s.[8] Most prominently, the Asian economic crisis drastically reduced the value of Asian currencies and allowed U.S. computer makers to buy many components cheaply. At the same time, DRAM producers had substantially increased their capacity, leading to a glut when expectations of increased demand were not fulfilled. (The combination of those two factors can be seen in Figure 3-1 with the rapid decline in DRAM costs in the late 1990s.)

The path of microprocessor prices also reveals the influence of transitory phenomena. Although microprocessor prices, as measured by BLS's producer price index, fell by a compound annual rate of 65 percent per year during 1999 and 2000, the rate was 39 percent for 2001.[9] Although both figures represent extremely rapid

7. Robert Doering,"Physical Limits of CMOS [Complementary Metal Oxide Semiconductor] Technology and ITRS [International Technology Roadmap for Semiconductors] Projections" (paper presented to the National Research Council Symposium on Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions, Kennedy School of Government, Harvard University, Cambridge, Mass., September 24, 2001).

8. The analysis is drawn from Kenneth Flamm, "Moore's Law and the Economics of Semiconductor Price Trends" (paper presented to the National Research Council Symposium on Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions, Kennedy School of Government, Harvard University, Cambridge, Mass., September 24, 2001; updated draft, December 2001). For a similar analysis, see McKinsey Global Institute, "Semiconductor," *Productivity in the United States, 1995-2000.*

9. Measured December to December. BLS changed its methodology for measuring the producer price index for microprocessors in 1998, so figures for previous years are not comparable.

rates of price decline, the difference is substantial.[10] Yet the fundamental nature of competition in the microprocessor market has not changed nor have any technological limits been reached.

TECHNOLOGICAL TRENDS FOR DISK DRIVES

The ordinary disk drive may be the unsung hero of the personal computer industry. Although integrated circuits get a great deal of attention because of their impressive price drops, disk drive manufacturers have produced similar or greater decreases in the unit memory costs in their product line. Every year, disk drive manufacturers make smaller, faster drives with higher storage capacity, and at lower prices (see Figure 4-1). Without that rapid rate of price decrease, the disk drive could have easily been replaced by specialized semiconductor memory circuits.

Disk drives have achieved those gains through improvements in two dimensions. First, the amount of information that manufacturers can squeeze into each square inch—areal density—has risen substantially. In fact, in the immediate past, areal density has increased 100 percent per year.[11] Second, the number of parts has been decreasing, further encouraging price cuts. For example, whereas hard drives previously had two or three spinning disks (platters), the leading-edge hard drives now often have only a single platter.[12]

Unlike the semiconductor industry with its *Roadmap*, the disk drive industry does not have a formal process for analyzing future trends, but analysts see no obvious impediment to continued improvements in the various parameters that influence storage costs overall. In order to continue their progress, firms in the industry may have to introduce new technology, such as new designs of read-write sensors and materials, but such advances have happened before.[13] As could be expected whenever the manufacturing technology changes, different firms are able

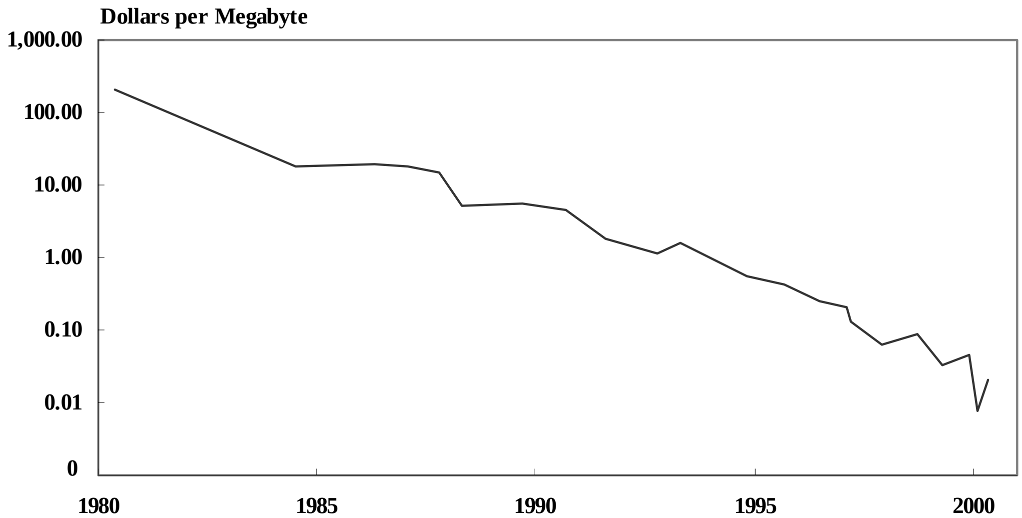
10. Industry observers have suggested that decreasing profit margins by Intel, and not pure technical change, were an important factor in the price reductions in the late 1990s. See Ana Aizcorbe, "Why Are Semiconductor Prices Falling So Fast? Industry Estimates and Implications for Productivity Measurement" (paper presented at the American Economic Association annual meeting, New Orleans, La., January 3-6, 2002).

11. E. Grochowski, "IBM Areal Density Perspective: 43 Years of Technology Progress," no date), available at www.storage.ibm.com/technolo/grochows/g03.htm.

12. In addition, the spin rate has been rising, lowering the time needed to access any given piece of information. Although that improvement does not affect the cost per unit of memory, it does affect performance and thus the value of the drive to the users.

13. Grochowski, "IBM Areal Density Perspective."

FIGURE 4-1. WHOLESALE PRICES FOR DISK DRIVES, 1980-2000



SOURCE: Congressional Budget Office based on data from IBM.

NOTE: The figure uses a logarithmic scale in the price axis. The prices at the beginning of the period are so much higher than those at the end—by close to five orders of magnitude—that presenting the same information using an arithmetic scale would obscure most of the price changes after the mid-1980s.

to make the requisite changes with different levels of success. Consequently, the names of the leading firms in the industry may change, but the overall level of competition and pace of technological improvements should remain the same.

FUTURE TRENDS IN THE DEMAND FOR COMPUTERS

In the preceding analysis of technological trends and the analysis of productivity growth that follows, CBO implicitly assumes not only that the technology of computers will improve but also that the uses to which consumers and businesses put computers will extend. In economic terms, both the supply and demand curves will shift outward simultaneously, although not necessarily by the same amount. That wider use of computers, CBO assumes, will compensate for the lower value that computer users would derive from applying improved computers in existing applications. For example, if increasingly powerful processors were applied solely to word processing, the benefits from additional processor speed would decline rapidly; however, faster processors can bring large benefits from emerging computer applications such as biotech research or speech recognition.

Some other analysts may find that assumption overly optimistic. For example, according to Robert Gordon, an economist at Northwestern University, the relationship between supply and demand has not changed in a way suggesting that the demand underlying current purchases of computers is substantially different from what it was a decade or more ago.[14] In economic terms, he believes that, while the supply curve has shifted dramatically, the demand curve has remained relatively stable. He argues that demand did not grow despite the decline in prices, because end users (businesses and consumers alike) quickly hit diminishing returns to investments in computers. After an initial boost, each additional increase in computing power has not permitted end users to write or analyze any more rapidly or with less effort or to perform their other tasks more efficiently. If that view is correct, the share of national output devoted to computers should stagnate or even decline in the near future. Productivity growth would be reduced relative to CBO's forecast.

Although at some point in the future, end users may not want many more or newer computers, the evidence does not yet suggest that they have reduced their demand for newer, more capable machines. Throughout the late 1990s, consumers bought more computer hardware and spent a larger fraction of national output on computer hardware each year. It is true that in 2001, end users bought less, but most industry analysts believe that the current downturn is cyclical and not a permanent shift in the quantity demanded. Furthermore, 2001 was not the first time that end users have reduced their computer purchases. During the recession in 1990, computer demand fell but then bounced back. CBO assumes that spending on computers will follow that pattern again, although not necessarily in detail.

As computing power declines in cost, the number of tasks that computers can economically perform rises. So the functions that dominated the use of computers two decades ago—word processing and spreadsheet calculations—no longer drive end users' buying decisions, even if the bulk of the work that users actually perform with computers remains unchanged. Rather, that wider range of tasks weighs more heavily in users' purchases.[15]

The nature of the new uses of computers also increases the demand for them. Some of the newer activities—surfing the Internet and corresponding through e-mail—increase communication among computers, which, some analysts argue, encourages end users to buy more-sophisticated computer hardware than the older

14. Robert Gordon, "Does the 'New Economy' Measure Up to the Great Inventions of the Past?" *Journal of Economic Perspectives*, vol. 4, no. 14 (Fall 2000), pp. 49-74.

15. Engineers and other product designers are also increasingly embedding microprocessors and other semiconductors in equipment of all types. As government statisticians extend their quality adjustment techniques to those other types of equipment, federal statistics may begin to record productivity gains in many other sectors of the economy as well.

uses, like word processing, would have suggested. Suppose, for example, that a business receives documents from its clients and suppliers that require the latest generation of computer software to read properly and that the requisite software runs properly only on the latest computer hardware. That business's decision about what hardware to buy must be based partly on what it is likely to receive from the outside and not just on its own internal needs. A few years ago, that same business would have received those documents in paper form by fax, mail, or messenger and would have decided on its software (and the attendant computer hardware) strictly on the basis of internal needs.

Finally, even if consumers and businesses in the future reduce the value that they attach to any single aspect of computing, such as a faster microprocessor, other components needed for performing the wide range of tasks demanded of computers (including connecting to the Internet, manipulating graphics, playing music, or downloading photographs) are all made with the same manufacturing technologies as the microprocessor is. So as end users increase their desire for those other features, they will continue to depend on advances in the technologies for manufacturing computer chips.

IMPLICATIONS FOR TOTAL FACTOR PRODUCTIVITY GROWTH

Purchases of computers affect changes in measured total factor productivity growth in two ways: through changes in the prices of the computers and through changes in the quantities of computers purchased.

As noted earlier, several temporary factors served to boost demand for computers during the late 1990s. The rapid growth of the Internet, the Y2K problem, and the need for firms to establish an initial presence on the Internet for electronic commerce all surfaced during that period. Those transitory factors accelerated investment in computers above its historical trend. Once those transitory factors ended, purchases of computers declined.[16] At the same time, the Bureau of Economic Analysis lowered its estimate of the level of overall investment in the economy for 1998 through 2000, especially for computers and other information technologies.

Like increases in the quantities of computers purchased, reductions in the prices of computers come from several sources. The rapid rate of price decline of the late 1990s can be thought of as having three parts: the underlying historical rate of price decline driven by technological change, transitory phenomena that comple-

16. Some analysts have argued that firms may have overestimated the number of computers they required to meet the needs of the growing Internet, producing a so-called overhang of perfectly good computers (and other electronic equipment) sitting idle or underused.

mented downward pressure on prices, and permanent changes in market structure that accentuated price competition in both computer systems and components. Only the transitory factors seem likely to abate in the foreseeable future, leading to the conclusion that the computer industry can expect an average rate of price decline that will be faster than what was experienced during the 1970-1995 period but less rapid than that occurring during the 1995-2000 time frame. Consequently, for its projections for 2003-2012, CBO assumes that some, but not all, of the increase in the rate at which computer prices declined in the late 1990s will remain.

CBO's projections of total factor productivity growth draw together three different sources: the trend rate of growth, an adjustment for the quality of computers, and an adjustment for some other changes in the economy and in federal statistics. In both the August 2001 projection and the January 2002 projection, the trend rate of growth of TFP is at 1.1 percent per year for the upcoming decade.[17] To that trend growth, CBO adds a factor to adjust for computer quality (as discussed earlier in Chapter 1). That addition represents the contribution to TFP growth made by the acceleration in technological progress in the computer manufacturing sector. CBO also adds an adjustment to compensate for changes in statistical techniques and other factors.

In its current (January 2002) projection, CBO assumes that quality improvements in computers will add 0.10 percentage points to TFP growth for the 2002-2012 period. That assumption implies that computer prices will continue to decline, although not as rapidly as they did in the late 1990s. CBO's belief that the share of GDP devoted to computer purchases will gradually rise during the upcoming decade also factors in the contribution of quality improvements. CBO also adds 0.09 percentage points to reflect changes in federal statistical techniques and in the cost of homeland security by private firms. With the adjustment for computer quality and the other adjustments, CBO's projection for annual growth in TFP is 1.28 percent (see Table 4-1).

If computer prices followed a different path from the one assumed for the period, then CBO's projection of TFP growth would change significantly. For instance, had CBO assumed that declines in computer prices would return to their 1973-1994 average of 14.4 percent per year, to adjust for computer quality CBO would have added just 0.04 percentage points to the annual trend growth rate in TFP (on the basis of current levels of demand for computers). Under that scenario, the annual TFP growth rate would fall, relative to CBO's base projection, to 1.22 percent. By contrast, if CBO assumed that the 24.2 percent annual decline in

17. Congressional Budget Office, *The Budget and Economic Outlook: An Update* (August 2001) and *The Budget and Economic Outlook, Fiscal Years 2003-2012* (January 2002).

TABLE 4-1. EFFECTS OF DIFFERENT PATHS FOR COMPUTER PRICES ON TOTAL FACTOR PRODUCTIVITY, 2002-2012 (In percent per year)

CBO's January 2002 Projection	
Trend Growth Rate	1.07
Adjustment for Computer Quality	0.10
Other Adjustments[a]	0.09
Total	1.28
Scenario Incorporating a Slower Decline in Computer Prices	
Trend Growth Rate	1.07
Adjustment for Computer Quality	
Using 1973-1994 Average Computer Price Decrease	0.04
Other Adjustments[a]	0.09
Total	1.22
Scenario Incorporating a Faster Decline in Computer Prices	
Trend Growth Rate	1.07
Adjustment for Computer Quality	
Using 1995-2001 Average Computer Price Decrease	0.18
Other Adjustments[a]	0.09
Total	1.36

SOURCE: Congressional Budget Office.

NOTE: All three projections assume the current level of investment in computers.

- Adjustments are for changes in federal statistical techniques as well as the economic slowdown caused by increased spending on homeland security by private firms.

computer prices of the 1995-2001 period continued, then the adjustment for computer quality would be 0.18 percentage points and annual TFP growth for the 2002-2012 span would be 1.36 percent. Thus, CBO's current calculation of an adjustment to TFP for computer quality—0.10 percentage points—lies slightly closer to a level based on the slower decline in computer prices before 1995 than to a level based on the more rapid decline in prices in the late 1990s.

APPENDIX A
HEDONIC PRICE ESTIMATION

The rapid technological progress in semiconductor and computer manufacturing can pose obstacles to measuring real price declines in computers. Because computers keep improving, the prices charged over time are, in a sense, for different products. For that reason, statisticians have come to rely on hedonic methods to supplement traditional price index methods.

For example, suppose a new computer enters the Bureau of Labor Statistics' producer price index to take the place of a discontinued model. (Replacement procedures in the consumer price index are similar but a bit more involved.) If the new and old models are different, price analysts typically try to obtain the difference in production costs between the two and use that as a proxy for differences in quality. However, gains in total factor productivity may make such information unavailable. For instance, thanks to technological advances, a new computer might offer twice the memory of its predecessor with no reported change in production costs.[1] Without alternative techniques for putting a value on that change in quality, however, the price index for the computer would show no price change upon its introduction. As a result, total factor productivity in the manufacture of computer hardware would be understated.

Such an implausible stability in computer prices led the Bureau of Economic Analysis, starting in mid-1980s, to apply hedonic price measurement techniques to its price deflator for computer equipment in the national income and product accounts. That approach allowed price comparisons to reflect technology-driven quality improvements in that equipment. The producer price index (since 1993), the international price program (since 1993), and the consumer price index (since 1998) all have used hedonic methodology to supplement standard methods for computer price indexes. The result is a composite price index, in which quality adjustments are based on exact (or "matched-model") comparisons of products, and production costs are used when available; hedonic methods are used when they are not.

Developing hedonic prices requires identifying the most important price-determining characteristics of products. Those characteristics are then used as explanatory variables in a statistical analysis—usually linear regression—to explain

1. Greater expenses might have been incurred in the past, when research and development was done to increase the capacity of the memory module, for instance. However, such expenses could be difficult for the producer to trace retrospectively and report for the sake of quality adjustments by the Bureau of Labor Statistics.

the prices. For example, such variables for personal computers might include processor type and speed, the amount of system and video memory, the hard drive capacity, multimedia features, operating and applications software, and computer manufacturer and warranty. The contribution of each characteristic to a product's price is estimated holding constant the association of all other features identified in the analysis. Those estimates thus reflect consumers' marginal valuation of each characteristic. Under perfect competition, that valuation also represents the resource cost to the producer, and the hedonic approach thus has a common footing with the Bureau of Labor Statistics' traditional methods.[2] (See Box A-1 for an example of this technique.)

Hedonic price techniques have figured perhaps most prominently in imputing real price changes from quality improvements in semiconductors and computers; much of the price change discussed in this report would have gone unmeasured without them. Certainly, because of that increased precision, expanding the number of products whose measured prices incorporate hedonic methods is a matter of considerable interest to the statistical community.[3]

---

2. One cannot necessarily assume perfect competition, especially in markets for high-technology products. As noted earlier, growth-accounting results are subject to similar qualifications. How the presence of imperfect competition in computer markets would bias the hedonic estimates and quality adjustments based on them is unclear. See Ariel Pakes, *A Reconsideration of Hedonic Price Indices with an Application to PCs*, NBER Working Paper No. W8715 (Cambridge, Mass.: National Bureau of Economic Research, January 2002).

3. See Brent Moulton, "The Expanding Role of Hedonic Methods in the Official Statistics of the United States," (paper presented at the Bureau of Economic Analysis Economic Advisory Meeting, November 2001), available at www.bea.doc.gov\bea\about\expand3.pdf; and Charles Schultze and Christopher Mackie, eds., *At What Price? Conceptualizing and Measuring Cost-of-Living and Price Indices* (Washington, D.C.: National Academy of Sciences Press, 2002). More and more European countries are also exploring the use of hedonic methods in their price index programs (see the Web site of the European Hedonic Centre's: www.zew.de/en/forschung/ projekte.php3?action =detail&nr=261).

BOX A-1.
AN EXAMPLE OF HEDONIC PRICE ESTIMATION IN THE PRODUCER PRICE INDEX

Suppose a new computer model introduced into the price index is identical to its predecessor in every way—including its price of $2,000—except that it offers an additional 256 megabytes (MB) of memory. The task is to factor out of the price comparison the quality improvement that the added memory represents.

If a hedonic regression estimated a value of $100 per 64MB of memory, then the additional 256MB of memory would represent a $400 quality difference. The base (or reference) price in the index for that product would be increased in proportion to the quality change: $400 / $2,000 = 0.20. Assume, for simplicity, that neither the attributes nor price of the old computer had changed since its introduction into the index and that it was the original item in that index category. Then its last reported price would also be the base price. The new computer price index comparison would show the following change:

$2,000 / ($2,000 x 1.20) = 0.83, or a real price decline of 17 percent.

If 100 computers were sold in the previous and current periods, then real computer output would increase as follows:

From: $200,000 / $2,000 = 100

To: $200,000 / ($2,000 x 0.83) = 120