

The Promise of Growth in the Information Age

Expanded version of 2002 Annual Essay

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The resurgence of the U.S. economy from 1995 to 2000 outran all but the most optimistic expectations. It is not surprising that the unusual combination of rapid growth and low inflation touched off a strenuous debate about the productivity of technology investment and whether improvements in U.S. economic performance could be sustained. This debate has intensified with the onset of recession, the collapse in technology company stock prices, and, more recently, with last summer's meltdown in the U.S. stock market.

The technological underpinnings of the last decade's remarkable economic performance should not be confused with the rapid pace of investment. The investment boom of the later 1990s was not sustainable, since it depended on substantially *more* growth in the number of hours people worked than in the labor force itself. Had the breakneck pace of investment continued, the economy would eventually have exhausted the pool of available labor. This is precisely what motivated the Federal Reserve to sharply increase interest rates beginning in May 1999, ending the boom and bringing on the mild recession that began in March 2001.

The investment boom and the productivity resurgence were driven by a remarkable decline in information technology (IT) prices. The decline in IT prices followed a dramatic acceleration in the semiconductor product cycle. The pace of technology that dramatically reduced the size of semiconductor devices opened up opportunities for technological advances in computers, communications, biosciences, and other IT-using industries. While advances in semiconductor technology found their broadest applications in computing and communications equipment, they have also reduced the cost and improved the performance of automobiles, aircraft, scientific instruments, and a host of other products. This process is likely to continue and even intensify.

Faster, Better, Cheaper

A mantra of the "new economy"—*faster, better, cheaper*—captures the speed of technological change and product improvement in semiconductors.

Modern information technology begins with the invention of the *transistor*, a semiconductor device that acts as an electrical switch and encodes information in binary form. Bell Labs constructed the first transistor, made of the semiconductor germanium, in 1947. The next major IT milestone was the co-invention of the *integrated circuit*, by Jack Kilby of Texas Instruments in 1958 and by Robert Noyce of Fairchild Semiconductor in 1959. An integrated circuit consists of many, even millions, of transistors that store and manipulate data in binary form. Originally developed for data storage, integrated circuits became known as *memory chips*. In 1965, Gordon E. Moore, then Research Director at Fairchild Semiconductor, made a prescient observation, later known as *Moore's Law*. He observed that each new chip contained roughly twice as many transistors as the previous one, and was released within 18–24 months of its predecessor. This implied exponential growth of capacity, at 35–45 percent per year!

When Moore and Noyce founded Intel Corporation in 1968 to speed the commercialization of memory chips, Moore became a key participant in realizing Moore's Law. Integrated circuits gave rise to microprocessors, or *logic chips*, with programmable functions. Intel developed its first general-purpose microprocessor for a calculator produced by Busicom, a Japanese firm. Intel retained the intellectual property rights and released the device commercially in 1971.

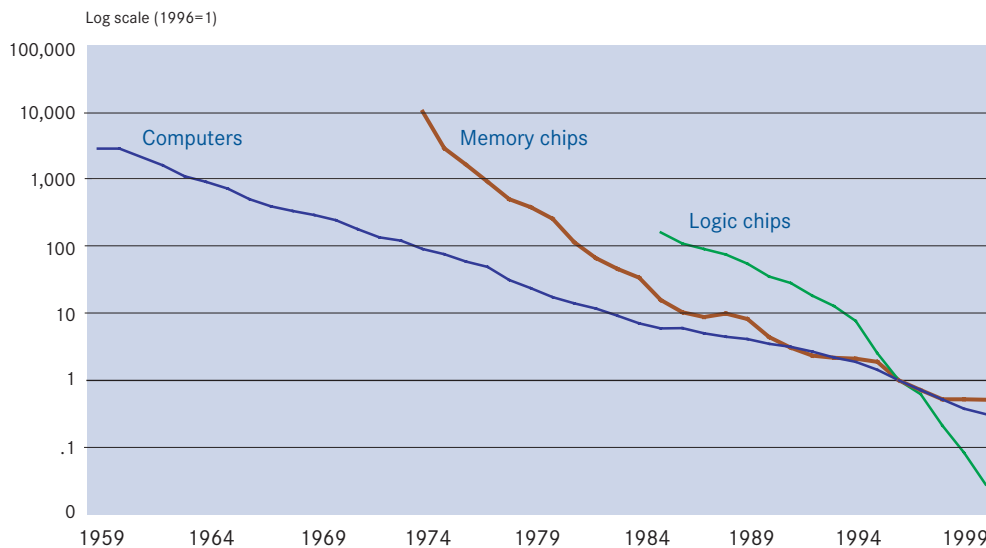
The rapidly rising capacities of microprocessors illustrate the exponential growth predicted by Moore's Law. The first logic chip, introduced in 1971, had 2,300 transistors; the Pentium 4, released by Intel in November 2000, had 42 million! Over this 29-year period, the number of transistors increased by 34 percent per year, tracking Moore's Law with astonishing accuracy.

Semiconductor Prices

Moore's Law also captures the fact that each successive generation of semiconductors is *faster* and *better*. This relentless improvement, continuing for three decades, makes the role of information technology in the U.S. economy unique. In both price measurements and to understand the sources of growth, the challenge for economics is to capture both the continuous improvement *and* the rapid pace of advance of semiconductor technology.

The economics of semiconductors begins with the observation that memory and logic chips have become cheaper at a truly staggering rate! Prices of memory chips *fell* by a factor of 27,270 times, or 40.9 percent per year, between 1974 and 1996. Similarly, prices of logic chips available for the shorter 1985–96 period declined by a factor of 1,938, or 54.1 percent per year (Chart 1).

Chart 1
Computer and semiconductor prices 1959–2000



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

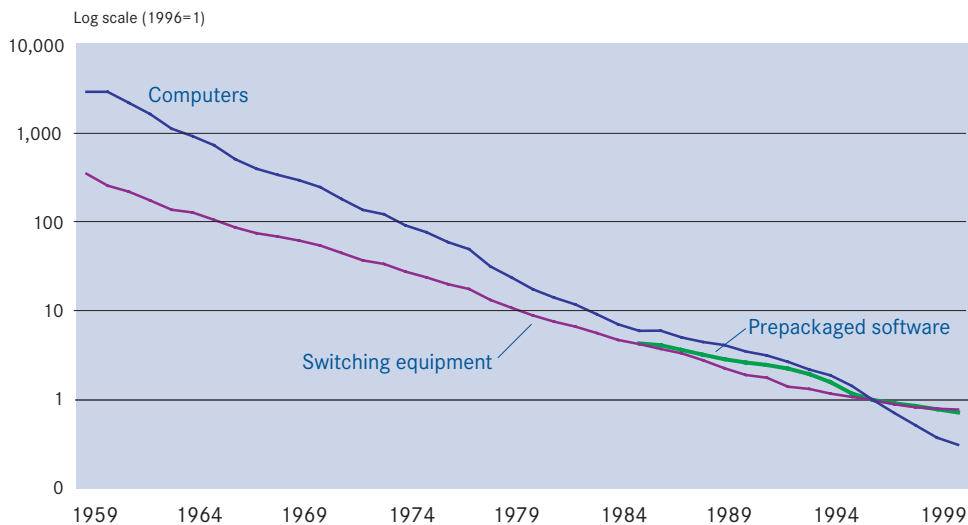
In 1994 and 1995 alone, the microprocessor price decline leapt to more than 90 percent per year as the semiconductor industry shifted from a three-year product cycle to a greatly accelerated two-year cycle. This is reflected in the 2001 edition of the *International Technology Road Map for Semiconductors*,¹ prepared by a consortium of industry associations.

Computer Prices

Intel’s 1978 sale of its 8086–8088 microprocessor to IBM for incorporation into the personal computer (PC) was a major business breakthrough. Three years later, in 1981, IBM licensed Microsoft’s MS-DOS operating system (Bill Gates and Paul Allen had founded that company in 1975). The same year, 1981, IBM introduced the PC—a watershed event in the deployment of information technology.

PCs and mainframe computers alike have come to rely heavily on logic chips for central processing, and memory chips for main memory. But semiconductors account for less than half of computer costs, and prices for computers have fallen much less rapidly than for semiconductors (the U.S. National Income and Product Accounts introduced precise computer price measures in 1985). The decline in computer prices follows the behavior of semiconductor prices, albeit in a much attenuated form (Chart 2). The accelerating decline of computer prices in 1995 mirrors a similar trend for semiconductor prices, which declined more quickly as a result of the 1995 changeover from a three-year product cycle to a two-year cycle.

Chart 2
Computer, communications, and software prices 1959–2000



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

¹ See *International Technology Roadmap for Semiconductors* (2001), online at <http://public.itrs.net>

Communications equipment prices

Extraordinary advances in computing power translate into tremendous potential cost reductions for downstream users. But users have only just begun to realize these reductions. Indeed, communications technology—one of the most important drivers of the technological revolution—has been undervalued because appropriate price measures have not been developed to capture the enormous gains in capability and, by implication, productivity. This technology is a crucial ingredient in the development and diffusion of the Internet, and perhaps the most striking manifestation of information technology in the U.S. economy.

Communications equipment is an important market for semiconductors, but constant performance price indexes have been developed only for switching equipment (see [Chart 2](#)) and terminal equipment. But much communications investment takes the form of the transmission gear connecting data, voice, and video terminals to switching equipment, fiber optics, microwave broadcasting, and communications satellites. Innovations in this equipment have progressed at rates that outrun even the dramatic pace of semiconductor development.

One such innovation is dense wavelength division multiplexing (DWDM), a technology that simultaneously sends multiple signals over an optical fiber. The installation of DWDM equipment, which began in 1997, has doubled the transmission capacity of fiber optic cables every 6–12 months. Yet we have no adequate price measures for capturing the value of this innovation to the economy. In other words, we are significantly underestimating the investment boom and the productivity gains from communications investment because our price measures are faulty.

Constructing price indexes that hold performance constant for communications equipment has been described as the “trench warfare” of economic statistics, since new data sources must be developed and exploited for each type of equipment. Had there been better measures of the true impact of communications investments, the extent of overcapacity might have been recognized at a much, much earlier stage and the recent implosion in the communications sector avoided.

Software prices

Software is also an increasingly important enabler in the technology space—rapidly growing expenditures here have made software investment much more important than investment in hardware. But here again, appropriate price measures—and accurate measures of the capacity that these investments generate—are lacking. The 11th comprehensive revision of the U.S. National Income and Product Accounts (NIPA), released in October 1999, re-classified computer software as investment.² Before this, business expenditures on software were simply omitted from the national product. These huge gaps in our ability to measure technological change challenge our ability to understand its impact on economic growth.

The revised national accounts now distinguish among three types of software—prepackaged, custom, and own-account. Prepackaged software (see [Chart 2](#)) is sold or licensed in standardized form, and delivered in shrink-wrapped packages or downloaded from the

² For a description of the 11th comprehensive revision of NIPA and the 1999 update, see Moulton (2000).

Internet. Custom software, which must be adapted, or “customized,” for individual users, facilitates business processes like database and human resource management, and cost accounting. Own-account software is written for specific purposes such as industrial process controls or airline reservations systems. Regrettably, price indexes hold performance constant only for prepackaged software, and this presents an additional challenge for economic measurement.

The Productivity Resurgence

The decline in semiconductor prices has been the driving force behind the U.S. economy’s accelerating growth in output and productivity since the mid 1990s. But the impact of this decline is *transmitted* through the prices of computers, communications equipment, and software. These products appear in the NIPA as investments by businesses, governments, and households, along with net exports to the rest of the world.

Table 1 summarizes, for major *output* categories, the growth rates of prices and quantities for 1990–95 and 1995–2000, with data based on the most recent benchmark revision of the national accounts, updated through 2000.³ The output concept is similar, but not identical, to the concept of gross domestic product (GDP) used in the U.S. national accounts. Both measures include final outputs purchased.

Table 1
Growth rates of outputs and inputs

	1990–95		1995–2000	
	Prices	Quantities	Prices	Quantities
Outputs				
Gross Domestic Product	2.10%	2.43%	1.40%	4.12%
Information technology	-4.35	12.15	-9.10	19.24
Computers	-15.77	21.71	-28.79	37.65
Software	-1.62	11.86	-1.54	16.50
Communications equipment	-1.77	7.01	-3.73	12.82
IT services	-2.71	12.18	-12.00	17.78
Non-IT investment	2.20	1.19	2.14	3.87
Non-IT consumption	2.47	2.15	2.01	3.03
Inputs				
Gross Domestic Income	2.34%	2.19%	2.08%	3.44%
IT capital services	-2.39	11.51	-10.97	18.97
Computers	-11.50	20.24	-28.30	35.84
Software	-1.56	12.68	-2.26	15.33
Communications equipment	2.57	5.44	-5.10	8.84
Non-IT capital services	2.45	1.78	1.69	3.04
Labor services	2.62	1.77	3.49	2.31

Note: Average annual percentage rates of growth.

³ For details on the estimates of outputs and inputs, see Jorgenson (2001).

The output measure used here also includes capital services (including the services of IT products) employed in the household and government sectors. The concept of capital services corresponds to the availability of a capital stock for a given period of time—an hour, a week, or a year. The *stock* of computers, for example, is the number of machines, while the *services* from a computer are measured in terms of the time the computer is available for use. It is convenient to measure computer services as the number of computers used per year, just as output is measured as the number of computers produced each year.

The most striking feature is the rapid price decline for computer investment, 15.8 percent per year from 1990 to 1995. Since 1995, this decline has nearly doubled, to 28.8 percent. That contrasts with relative software prices, which fell only 1.6 percent per year from 1990 to 1995 and 1.5 percent thereafter. Communications equipment prices behave similarly to software prices.

[Table 1](#) also summarizes the growth rates of prices and quantities of capital *inputs* for the same periods. In response to continuing price declines, firms, households, and governments have accumulated computers, software, and communications equipment much more rapidly than other forms of capital. Growth in IT capital services reflects the impact of these growing stocks on U.S. economic output. While the growth in non-IT capital services increased from 1.8 percent to 3 percent, growth in IT capital services jumped from 11.5 percent per year in 1990–95 to 19 percent in 1995–2000.

The capital service price for computers fell 28.3 percent per year for 1995–2000, compared to an increase of 35.8 percent in capital input from computers. Consequently, the value of computer services grew substantially. But in 2000, the current dollar value of computers was only 1.4 percent of gross domestic income.

The rapid accumulation of software appears to have different sources. The price of software services declined only 2.3 percent per year for 1995–2000. Firms have been accumulating software very rapidly, nonetheless, with real capital services growing 15.3 percent per year. One possible explanation is that firms respond to computer price declines by investing in complementary inputs like software. Another is that the price indexes for software investment fail to hold performance constant, leading to an overstatement of inflation and an understatement of growth.

Although the price decline for communications equipment during 1995–2000 is comparable to that for software, investment in this equipment is more in line with prices. But constant performance price indexes are unavailable for transmission gear such as fiber-optic cables. This leads to an underestimate of the growth rates of investment, capital services, and the GDP, as well as an overestimate of the rate of inflation.

Accounting for growth

Economists identify the contributions of outputs and inputs to U.S. economic growth by means of *growth accounting*. The GDP growth rate is a weighted average of the growth rates of the outputs of investment and consumption goods. In a system of growth accounts for the U.S. economy, the *contribution* of each output is its growth rate weighted by its share in the value of the GDP. Similarly, the growth rate of input is a weighted average of the growth rates of capital and labor services; the *contribution* of each input is its weighted growth rate.

The final component of a system of growth accounts is growth in *total factor productivity* (TFP), defined as output per unit of input (including both capital and labor inputs). Economies increase the productivity of both labor and capital by pushing out the technological frontier.

The results of growth accounting can also be presented in terms of *average labor productivity* (ALP), defined as the ratio of output to hours worked. The growth in ALP can be allocated among three sources. The first is *capital deepening*, the growth in capital input per hour worked, reflecting the substitution of cheaper capital for more expensive labor. The second, *improvement in labor quality*, captures the rising proportion of hours by workers with higher productivity. The third component adds a percentage point to ALP growth for each percentage point of TFP growth.

Massive increases in computing power, like those experienced by the U.S. economy, have the potential to extend the technological frontier and drive growth in two ways. First, as IT *producers* become more efficient, more IT equipment and software is produced from the same inputs. This raises productivity in IT-producing industries and contributes to TFP growth for the economy as a whole. Labor productivity also grows at both industry and aggregate levels.

Second, investment in information technology leads to growth of productive capacity in IT-*using* industries.⁴ Labor is working with more and better equipment, and this increases ALP through capital deepening. If the contributions to aggregate output are entirely captured by capital deepening, aggregate TFP growth is unaffected, since output per unit of input remains unchanged.

But major technological advances can increase productivity even when capital deepening is taken into account.

⁴ For a list of IT-producing industries, see Economics and Statistics Administration (2002), Table 3.1, p. 25.

Unlocking the Future With the Past

To understand the distinctive features of economic growth since 1995, we need to examine the sources of the growth of the U.S. economy for the past half-century and see how our recent experience compares. [Table 2](#) presents results of a growth accounting decomposition for 1948–2000 and various sub-periods. Economic growth is broken down by output and input categories, quantifying IT’s contribution to investment and consumption outputs, as well as to capital inputs. These estimates are based on computers, software, and communications equipment as distinct types of information technology.

Capital input contributes 1.7 percentage points to GDP growth, labor input 1.1 percentage points, and TFP growth only 0.6 percentage points for the entire 1948–2000 period. Not surprisingly, input growth is the source of nearly 82.5 percent of the 3.5 percent per year GDP growth over the last 50 years. The ability to combine labor and capital in innovative ways—TFP—accounted for only 17.5 percent of growth during that period ([Chart 3](#)). In other words, the economy grew largely because we put more people to work, they worked longer hours, they were better educated, and, most significantly, they worked with more and better capital. How labor and capital are combined to achieve new ways of doing business accounts for a much smaller share of long-term growth.

A look at the U.S. economy before and after 1973 reveals familiar features of the historical record. After strong output and TFP growth in the 1950s, 1960s and early 1970s, the U.S. economy slowed markedly during 1973–90, with output growth falling from 4 percent for 1948–73 to 2.9 percent for 1973–90, and TFP growth declining from 0.9 percent to just under a quarter percent. The contribution of capital inputs also slowed from 1.9 percent to 1.5 percent.

Dating the ascendancy

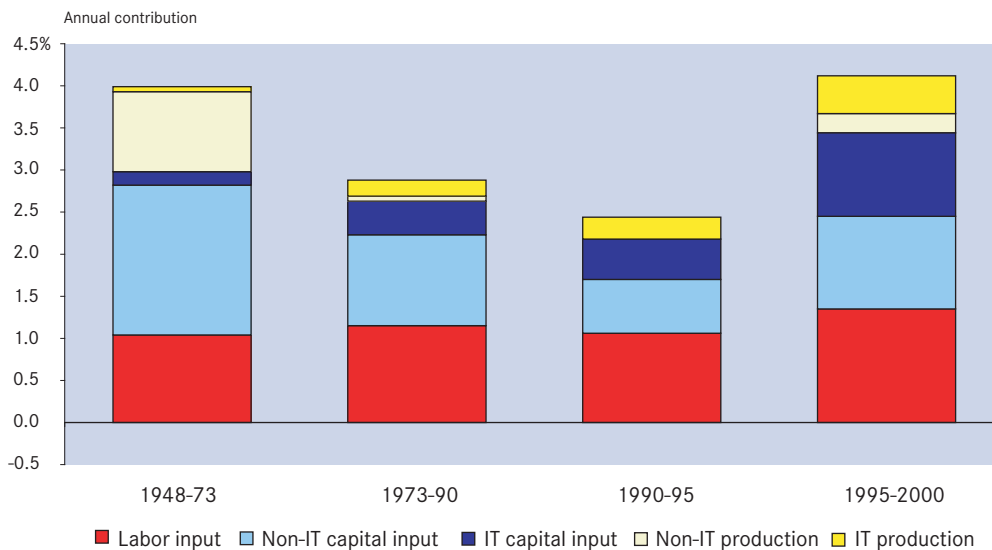
Although the contribution of IT has increased steadily throughout the 1948–2000 period, there was a sharp and easily recognizable response to the acceleration in the IT price decline in 1995. Relative to the early 1990s, output growth increased by 1.7 percent in 1995–2000. IT production accounted for only 26.9 percent of this increase, although the contribution of IT production almost doubled. Almost three-quarters of the increased output growth can be attributed to non-IT products.

That said, the accelerating decline of IT prices signals faster *productivity* growth in IT-producing industries—industries that have been the source of most productivity growth throughout the 1990s. The IT-producing industries have accounted for about half the surge in productivity growth since 1995 (far greater than the 6.5 percent share of IT in the 2000 GDP).

Before 1995, this was due to the decline of productivity growth elsewhere in the economy. [Table 3](#) reveals the well-known productivity slowdown of the 1970s and 1980s and depicts the acceleration in labor productivity growth in the late 1990s. The slowdown through 1990 reflects reduced capital deepening, declining labor quality growth, and decelerating growth in TFP. This contributed to the sluggish ALP growth of 2.8 percent for 1948–73, but only 1.3 percent for 1973–90.

Sources of GDP Growth

Chart 3



Note: Input contributions are average annual rates of growth, weighted by average nominal income shares.

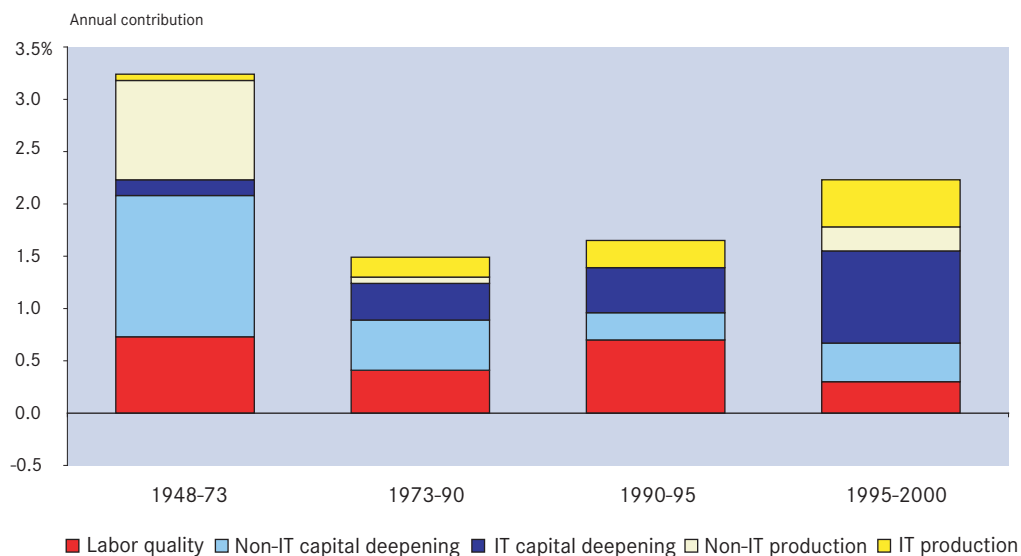
Table 2

	1948-2000	1948-73	1973-90	1990-95	1995-2000
Outputs					
Gross Domestic Product	3.49%	3.99%	2.87%	2.43%	4.12%
Contribution of information technology	0.40	0.20	0.45	0.57	1.11
Computers	0.12	0.04	0.16	0.18	0.35
Software	0.08	0.02	0.09	0.15	0.31
Communications equipment	0.10	0.08	0.10	0.09	0.20
IT services	0.10	0.06	0.10	0.15	0.25
Contribution of non-IT	3.08	3.79	2.42	1.86	3.01
Investment	0.72	1.06	0.36	0.22	0.76
Consumption	2.36	2.74	2.06	1.64	2.25
Inputs					
Gross Domestic Income	2.83%	2.98%	2.63%	2.19%	3.44%
Contribution of IT capital services	0.35	0.16	0.40	0.48	0.99
Computers	0.16	0.04	0.20	0.22	0.54
Software	0.08	0.02	0.08	0.16	0.28
Communications equipment	0.11	0.10	0.12	0.10	0.17
Contribution of non-IT capital services	1.38	1.78	1.08	0.64	1.10
Contribution of labor services	1.11	1.04	1.15	1.06	1.35
Total Factor Productivity (TFP)	0.65	1.01	0.25	0.24	0.68

Note: Average annual percentage rates of growth. The contribution of an output or input is the rate of growth multiplied by the value share.

Sources of Average Labor Productivity (ALP) Growth

Chart 4



Note: Contributions are from Table 3.

Table 3

	1948-2000	1948-73	1973-90	1990-95	1995-2000
Gross Domestic Product	3.49%	3.99%	2.87%	2.43%	4.12%
Hours worked	1.32	1.06	1.55	1.08	2.01
Average labor productivity	2.17	2.92	1.32	1.35	2.11
Contribution of capital deepening	1.18	1.50	0.83	0.70	1.25
Information technology	0.31	0.15	0.35	0.43	0.88
Non-IT	0.87	1.35	0.48	0.26	0.37
Contribution of labor quality	0.34	0.42	0.24	0.42	0.18
Total Factor Productivity (TFP)	0.65	1.01	0.25	0.24	0.68
IT	0.16	0.06	0.19	0.26	0.45
Non-IT	0.49	0.95	0.06	-0.02	0.23

Addendum

Labor input	1.90%	1.79%	1.96%	1.77%	2.31%
Labor quality	0.58	0.73	0.41	0.70	0.30
Capital input	4.14	4.61	3.59	2.79	5.03
Capital stock	3.31	4.10	2.74	1.84	2.75
Capital quality	0.83	0.51	0.85	0.95	2.28

Note: Average annual percentage rates of growth.

The growth of ALP slipped further during the early 1990s, with a slump in capital deepening only partly offset by a revival in labor quality growth and an up-tick in TFP growth. A slowdown in hours combined with slowing ALP growth during 1990–95 to produce a further slide in the growth of output. In previous cyclical recoveries during the postwar period, output growth accelerated during the recovery, powered by more rapid growth of hours and ALP.

Accelerating output growth during 1995–2000 reflects growth in labor hours and ALP almost equally. Growth in ALP rose 0.9 percent, as more rapid capital deepening and growth in TFP offset slower improvement in labor quality. Growth in hours worked accelerated as unemployment fell to a 30-year low. Labor markets have tightened considerably, even as labor force participation rates increased.

Comparing 1990–95 to 1995–2000, the rate of output growth jumped by 1.7 percent, due to an increase in hours worked of 0.8 percent and another increase in ALP growth of 0.9 percent. As [Chart 4](#) shows, the acceleration in ALP growth is due to capital deepening as well as faster TFP growth. Capital deepening contributed 0.6 percentage points, offsetting a negative contribution of labor quality of a quarter percent. The acceleration in TFP added 0.5 percentage points.

The calculus of labor and capital

Indeed, both labor *and* capital made significant contributions to the growth surge of the late 1990s. The growth rate of labor input accelerated to about two and a quarter percent for 1995–2000 from just under 1.9 percent for 1990–95 (see [Table 1](#)). This is primarily due to the growth of hours worked, which rose from 1.2 percent for 1990–95 to 2 percent for 1995–2000, as labor force participation increased and unemployment rates plummeted (see [Table 3](#); The distinction between labor input and labor hours is analogous to the distinction between capital services and capital stock.. The growth in labor quality is the difference between the growth in labor input and hours worked. Labor quality reflects the increased relative importance of workers with higher productivity.).

The growth of labor quality declined considerably in the late 1990s, dropping from 0.7 percent for 1990–95 to just over a quarter percent for 1995–2000. With exceptionally low unemployment rates, employers were forced to add workers with limited skills and experience.

But using the U.S. labor force more intensively was far from the whole story.

Capital investment has been the most important source of U.S. economic growth throughout the postwar period. The relentless decline in the prices of information technology equipment has steadily enhanced the role of IT investment. This, in turn, has given additional weight to the most highly productive components of capital. Compared to a 0.2 percent rise in the contribution of labor input and a TFP acceleration of 0.5 percent between 1990–95 and 1995–2000, the contribution of capital input jumped by almost one percentage point. This latter contribution reflects the investment boom of the late 1990s, when

businesses, households, and governments poured resources into plant and equipment—especially computers, software, and communications equipment. The jump in the contribution of capital input since 1995 boosted growth by nearly a full percentage point, and IT accounts for more than half of this increase.

The acceleration in U.S. economic growth after 1995 and the enormous contribution of capital to this acceleration is unmistakable. The relationship of information technology to these is now transparent. The most important contribution of IT is through faster growth of capital input, reflecting higher rates of investment. This growth in capital is due not just to the quantity of capital stock but its increasing *quality*, i.e., capital input per unit of capital stock.

This improvement in capital quality represents the substitution of assets with higher productivity, such as IT assets, for those with less. The growth of capital quality is slightly less than twenty percent of capital input growth for the period 1948–95. But improvements in capital jumped to 45.3 percent of total growth in capital input during the 1995–2000 period, reflecting very rapid restructuring of capital to take advantage of the sharp acceleration in the IT price decline.

Finally, the increased ability to combine labor and capital in productive ways was a major boost to growth at the end of the 1990s. Investment and labor utilization was higher, but it was also more productive—largely because of the technology revolution. After maintaining an average rate of a quarter percent for the 1973–90 period, TFP growth continued at 0.2 percent for 1990–1995, then vaulted to 0.7 percent per year for 1995–2000. This increase is an important source of the output growth in output of the U.S. economy (see [Chart 3](#)). While TFP growth for 1995–2000 is lower than the rate for 1948–73, the U.S. economy is definitely recuperating from the anemic productivity growth of the previous two decades. The question is whether this improvement is sustainable.

What Happens Next?

Falling IT prices will continue to provide incentives for substituting IT for other productive inputs. The decline in IT prices will also serve as an indicator of ongoing productivity growth in IT-producing industries. But it would be premature to extrapolate the recent acceleration in productivity growth into the indefinite future, since this depends on the persistence of a two-year product cycle for semiconductors.

The economic forces that underlie the two-year cycle reflect intensifying competition among semiconductor producers in the United States and around the world. If this rapid rate of technological progress is to persist over the next decade, new technologies must be exploited. This is already generating a massive research and development effort that will strain the financial capacities of the semiconductor industry and its equipment suppliers.

The 2001 edition of the *International Technology Roadmap for Semiconductors* projects a two-year product cycle through 2005 and a three-year cycle thereafter. This seems to be a reasonable basis for projecting the growth of the U.S. economy—a continued two-year cycle provides an upper bound for growth projections, while reversion to a three-year cycle gives a lower bound. The range is useful for suggesting just what an uncertain business it is to project U.S. economic growth into the next decade or so.

The key assumption for such intermediate-term projections is that output and capital stock grow at the same rate—characteristic of the United States and most industrialized economies over periods longer than a typical business cycle. In this scenario, the growth of output is the sum of the growth rates of hours worked and labor quality, plus the contributions of capital quality growth and TFP growth. A projection of U.S. economic growth depends on the outlook for each of these four components.

Demographic trends...

During 1995–2000, hours worked grew nearly 2 percent per year—almost double that of the labor force. Future growth in hours worked will inevitably track the growth of the labor force, which, dependent as it is on population demographics (and therefore highly predictable), will average only 1.1 percent per year for the next decade. Growth of labor quality during 1995–2000 dropped to a quarter percent per year and will revive, modestly, to 0.3 percent per year, reflecting ongoing improvements in the productivity of individual workers. The overall growth rate of labor input over the next decade will thus average 1.4 percent per year. This contrasts with the two and a quarter percent growth rate of 1995–2000, which reflects nonrecurring declines in the rate of unemployment and one-time increases in the rates of labor force participation.

...and a longer product cycle...

The second part of a growth projection requires assumptions about the growth in TFP and capital quality. So long as the two-year product cycle for semiconductors continues, TFP growth is likely to average 0.7 percent per year, the rate during 1995–2000. With a three-year product cycle, growth in TFP might drop as low as 0.2 percent per year, the rate during 1990–95, reflecting the slower pace of technological change.

The contribution of capital quality reflects the rapid substitution of IT for non-IT assets in response to declining IT prices. The growth of capital quality will continue at the recent rate of 2.3 percent per year, so long as the two-year product cycle for semiconductors persists. But this rate will drop to 1 percent per year under the assumption of a three-year product cycle, generating considerable uncertainty about future growth.

Assuming continuation of a two-year product cycle for semiconductors through 2005 and a three-year product cycle after that, the intermediate-term growth rate of the U.S. economy will be 3.4 percent per year. The upper bound on this growth rate, associated with continuation of a two-year product cycle, is 3.8 percent per year; the lower bound, associated with a two-year product cycle, is 2.4 percent per year.

...temper expectations

In other words, a return to the 4.1 percent per year growth rate during the resurgence of 1995–2000 is extremely unlikely. This would require not only a continued rapid pace of technological advance, but also growth in employment that would soon exhaust the available force. But it is important to emphasize that U.S. growth prospects have improved considerably. The average growth rate of 1973–90 was 2.9 percent per year, and the growth rate from 1990–95 was only 2.4 percent per year—the lower bound of estimates consistent with more recent experience.

Better data, better policy, better future

The benefits of IT are real and tangible, and the performance of the IT industries is crucial to future growth prospects. While recognizing the enormous benefits of the future development and diffusion of IT, we must give close attention to the uncertainties that surround this. We must give the highest priority to better understanding both the markets for semiconductors and, especially, the determinants of the product cycle. Improved data on the prices of telecommunications and software are essential to understanding the links between semiconductor technology and the growth of the U.S. economy.

The semiconductor industry and IT industries are global in their scope, with an elaborate international division of labor.⁵ This poses important questions about the U.S. growth resurgence. We lack evidence on IT's impact on other leading industrialized countries, and we do not fully understand the future roles of important IT participants such as Korea, Malaysia, Singapore, and Taiwan—all “newly industrializing” economies. Moreover, what will IT's economic impact be on developing countries like China and India?

Information technology is altering product markets and business organizations, as attested by the huge and rapidly growing business literature,⁶ but a fully satisfactory model of the semiconductor industry has yet to be developed. Such a model would have to derive the demand for semiconductors from investment in IT, and determine the product cycle for successive generations of new semiconductors.

As policy makers attempt to fill the widening gaps between the information required for sound policy and the available data, the traditional division of labor between statistical agencies and policy-making bodies is breaking down. The Federal Reserve has recently undertaken a major research program on constant performance IT price indexes. In the meantime, monetary policy makers must set policies without accurate measures of price change. Likewise, fiscal policy makers confront ongoing revisions of growth projections that drastically affect the outlook for future tax revenues and government spending.

The unanticipated U.S. growth revival of the 1990s has considerable potential for altering economic perspectives. In fact, a steady stream of excellent books on the economics of information technology already foreshadows this.⁷ Economists are the fortunate beneficiaries of a new agenda for research that could refresh their thinking and revitalize their discipline. Their insights will be essential to reshaping economic policy so that everyone can take advantage of the opportunities that lie ahead.

⁵ The role of information technology in U.S. economic growth is discussed by the Economics and Statistics Administration (2002); comparisons among OECD countries are given by Colecchia and Schreyer (2002).

⁶ See Grove (1996) on the market for computers and semiconductors; and Christensen (1997) on the market for storage devices.

⁷ See Shapiro and Varian (1999), Brynjolfsson and Kahin (2000), and Choi and Whinston (2000).

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