American Economic Growth in the Information Age

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The resurgence of the American economy since 1995 has outrun all but the most optimistic expectations. It is not surprising that the unusual combination of more rapid growth and slower inflation in the 1990's has touched off a strenuous debate among economists about whether improvements in America's economic performance can be sustained. This debate has been intensified by the recent growth slowdown.

A consensus is building that the remarkable decline in IT prices provides the key to the surge in American economic growth. In the following section I show that the IT price decline is rooted in developments in semiconductor technology that are widely understood by technologists and economists. This technology has found its broadest applications in computing and communications equipment, but has reduced the cost and improved the performance of aircraft, automobiles, scientific instruments, and a host of other products.

Sharp decline in IT prices is the key to the surge in economic growth

Price indexes for IT that hold performance constant are necessary to separate the change in performance of IT equipment from the change in price for a given level of performance. Accurate and timely computer prices have been part of the U.S. National Income and Product Accounts (NIPA) since 1985. Unfortunately, important information gaps remain, especially on trends in prices for closely related investments, such as software and communications equipment.

In Section II I outline a framework for analyzing the role of information technology in the American growth resurgence. This framework treats IT equipment as part of the output of investment goods and capital services from this equipment as a component of capital input. A measure of capital services captures the impacts of rapidly growing stocks of computers, communications equipment, and software on the output of the U.S. economy.

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

The investment boom of the later 1990's was not sustainable, since it depended on growth in hours worked in excess of labor force growth. Nonetheless, growth prospects for the U.S. economy have improved considerably, due to enhanced growth of productivity in IT production and continuing substitution of IT assets for non-IT assets in response to falling IT prices. Section III concludes the paper.

The Information Age

A mantra of the "new economy" – *faster, better, cheaper* – captures the speed of technological change and product improvement in semiconductors and the precipitous and continuing fall in semiconductor prices. 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. The first transistor, made of the semiconductor germanium, was constructed at Bell Labs in 1947.

The next major milestone in information technology was the co-invention of the *integrated circuit* by Jack Kilby of Texas Instruments in 1958 and Robert Noyce of Fairchild Semiconductor in 1959.

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An integrated circuit consists of many, even millions, of transistors that store and manipulate data in binary form. Integrated circuits were originally developed for data storage and these semiconductor devices 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*. Plotting data on memory chips, he observed that each new chip contained roughly twice as many transistors as the previous chip and was released within 18–24 months of its predecessor. This implied exponential growth of chip capacity at 35–45 percent per year!

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

The rapidly rising capacities of microprocessors and storage devices illustrate the exponential growth predicted by Moore's Law. The first logic chip in 1971 had 2,300 transistors, while the Pentium 4, released by Intel on November 20, 2000, had 42 million! Over this twenty-nine year period the number of transistors increased by thirty-four percent per year.

Semiconductor Prices

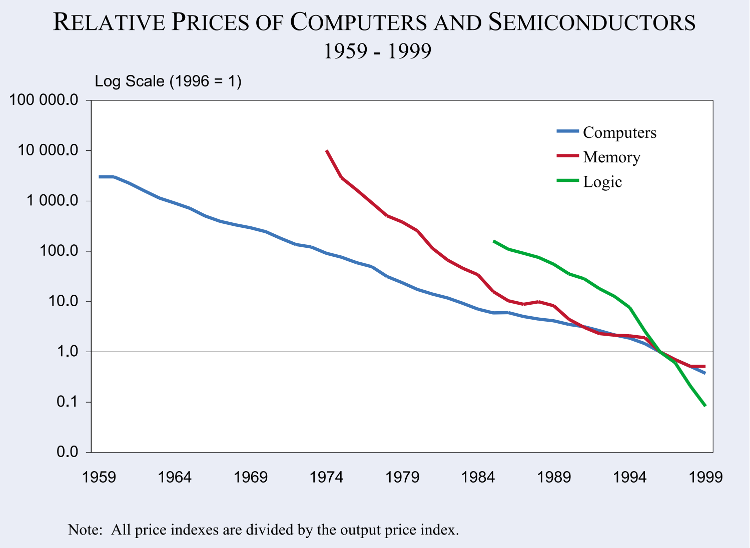
Moore's Law captures the fact that successive generations of semiconductors are *faster and better*. The economics of semiconductors begins with the closely related observation that memory and logic chips have become *cheaper* at a truly staggering rate! Chart 1 gives semiconductor price indexes employed in the U.S. national accounts since 1996. These are divided between memory chips and logic chips.

Prices of memory chips, holding performance constant, *decreased* by a factor of 27,270 times or 40.9 percent per year between 1974 and 1996. Similarly, prices of logic chips that hold performance constant, available for the shorter period 1985 to 1996, *decreased* by a factor of 1,938 or 54.1 percent per year. Semiconductor price declines closely parallel Moore's Law on the growth of chip capacity.

Chart 1 also reveals a sharp acceleration in the decline of semiconductor prices in 1994 and 1995. The microprocessor price decline leapt to more than ninety 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 **2000 Update** of the International Technology Road Map for Semiconductors[1], prepared by a consortium of industry associations.

Prices of semiconductors decreased rapidly

Chart 1



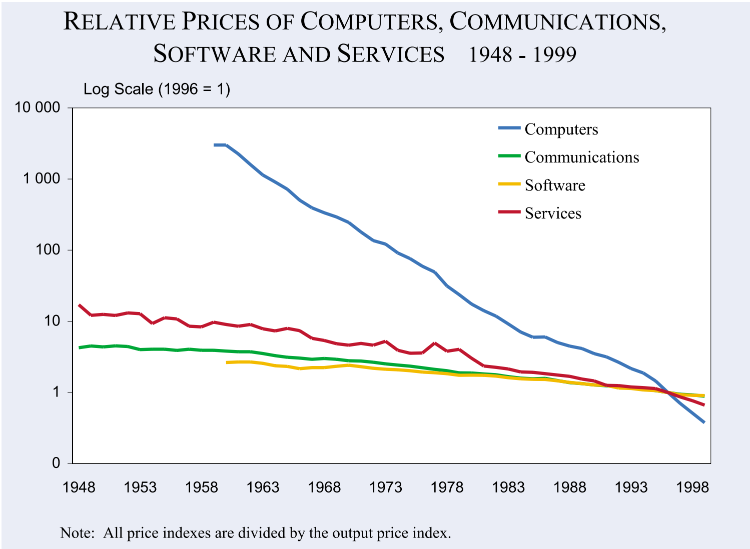
Computer Prices

The introduction of the Personal Computer (PC) by IBM in 1981 was a watershed event in the deployment of information technology. The sale of Intel's 8086-8088 microprocessor to IBM in 1978 for incorporation into the PC was a major business breakthrough for Intel. In 1981 IBM licensed the MS-DOS operating system from the Microsoft Corporation, founded by Bill Gates and Paul Allen in 1975.

Mainframe computers, as well as PC's, have come to rely heavily on logic chips for central processing

[1] On International Technology Roadmap for Semiconductors (2000), see: http://public.itrs.net/.

Chart 2



and memory chips for main memory. However, semiconductors account for less than half of computer costs and computer prices have fallen much less rapidly than semiconductor prices. Precise measures of computer prices that hold product performance constant were introduced into the U.S. National Income and Product Accounts in 1985.

The decline in computer prices follows the behavior of semiconductor prices – but at a slower pace

Chart 2 gives a constant performance price index of computers and peripheral equipment and its components, including mainframes, PC's, storage devices, other peripheral equipment, and terminals. The decline in computer prices follows the behavior of semiconductor prices presented in Chart 1, but in much attenuated form. The 1995 acceleration in the computer price decline mirrors the acceleration in the semiconductor price decline that resulted from the changeover from a three-year product cycle to a two-year cycle in 1995.

Communications equipment and software prices

Communications technology is crucial for the rapid development and diffusion of the Internet, perhaps the most striking manifestation of information technology in the American economy. Communications equipment is an important market for semiconductors, but constant performance price indexes cover only switching and terminal equipment. Much communications investment takes the form of the transmission gear, connecting data, voice, and video terminals to switching equipment.

Technologies for transmission, such as fiber optics, microwave broadcasting, and communications satellites, have progressed at rates that outrun even the dramatic pace of semiconductor development. An example is dense wavelength division multiplexing (DWDM), a technology that sends multiple signals over an optical fiber simultaneously. Installation of DWDM equipment, beginning in 1997, has doubled the transmission capacity of fiber optic cables every 6–12 months.

Both software and hardware are essential for information technology and this is reflected in the large volume of software expenditures. The eleventh comprehensive revision of the U.S. National Income and Product Accounts, released on October 27, 1999, re-classified computer software as investment.[2] Before this important advance, business expenditures on software were simply omitted from the national product, leaving out a critical component of IT investment.

Software investment is growing rapidly and is now much more important than investment in computer hardware. The revised national accounts now distinguish among three types of software – prepackaged, custom, and own-account software. Unfortunately, only price indexes for prepackaged software hold performance constant. Prepackaged software is sold or licensed in standardized form and is delivered in shrink-wrapped packages or electronic files downloaded from the Internet.

An important challenge for economic measurement is to develop price indexes that hold performance constant for all of telecommunications equipment and software. This has been described as the "trench warfare" of economic statistics, since new data sources must be developed and exploited for each type of equipment and software. Until comprehensive price indexes are available, our picture of the role of information technology in U.S. economic growth will remain incomplete.

[2] Moulton (2000) describes the 11th comprehensive revision of NIPA and the 1999 update.

The American Growth Resurgence

The American economy has undergone a remarkable resurgence since the mid-1990's with accelerating growth in output and productivity. My next objective is to quantify the sources of growth for 1948–99 and various sub-periods. My primary focus is the sharp acceleration in the level of economic activity since 1995 and, in particular, the role of information technology.

While semiconductor technology is the driving force behind the spread of IT, the impact of the relentless decline in semiconductor prices is transmitted through falling IT prices. Only net exports of semiconductors, defined as the difference between U.S. exports to the rest of the world and U.S. imports appear in the GDP. Accordingly, I focus on the role of computers, communications equipment and software rather than semiconductors in analyzing U.S. economic growth.

At the aggregate level IT is identified with the outputs of computers, communications equipment, and software. These products appear in the GDP as investments by businesses, households, and governments along with net exports to the rest of the world. The GDP also includes the services of IT products consumed by households and governments.

Economic Growth

The output data in Table 1 are based on the most recent benchmark revision of the national accounts, updated through 1999.[3] The output concept is similar, but not identical, to the concept of gross domestic product used in the U.S. national accounts. Both measures include final outputs purchased by businesses, governments, households, and the rest of the world. The output measure in Table 1 also includes the services of durable goods, including IT products, employed in the household and government sectors.

The top panel of Table 1 summarizes the growth rates of prices and quantities for major output categories for 1990-5 and 1995-9. 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 more than doubled to 32.1 percent per year. By contrast the relative price of software fell only 1.6 percent per year from 1990 to 1995 and 2.4 percent per year since 1995. The price of communications equipment behaves similarly to the software price, while the price of information technology services falls between hardware and software prices.

The second panel of Table 1 summarizes the growth rates of prices and quantities of capital inputs for 1990-5 and 1995-9. In response to the price changes, firms, households, and governments have accumulated computers, software, and communications equipment much more rapidly than other forms of capital. Growth of IT capital services jumped from 11.51 percent per year in 1990-5 to 19.41 percent in 1995-9, while growth of non-IT capital services increased from 1.72 percent to 2.94 percent.

The drop in prices has induced a higher accumulation of computers

Table 1 describes the rapid increase in the importance of IT capital services, reflecting the impact of growing stocks of computers, communications equipment, and software on the output of the U.S. economy. In 1995-9 the capital service price for computers fell 24.8 percent per year, compared to an increase of 36.4 percent in capital input from computers. As a consequence, the value of computer services grew substantially. However, the current dollar value of computers was only 1.6 percent of gross domestic income in 1999.

The rapid accumulation of software appears to have different

Table 1

Growth Rates of Outputs and Inputs

	1990-95		1995-99	
	Prices	Quantities	Prices	Quantities
	Outputs			
Gross Domestic Product	1,99	2,36	1,62	4,08
Information Technology	-4,42	12,15	-9,74	20,75
Computers	-15,77	21,71	-32,09	38,87
Software	-1,62	11,86	-2,43	20,80
Communications Equipment	-1,77	7,01	-2,90	11,42
Information Technology Services	-2,95	12,19	-11,76	18,24
Non-Information Technology Investment	2,15	1,22	2,20	4,21
Non-Information Technology Consumption	2,35	2,06	2,31	2,79
	Inputs			
Gross Domestic Income	2,23	2,13	2,36	3,33
Information Technology Capital Services	-2,70	11,51	-10,46	19,41
Computer Capital Services	-11,71	20,27	-24,81	36,36
Software Capital Services	-1,83	12,67	-2,04	16,30
Communications Equipment Capital Services	2,18	5,45	-5,90	8,07
Non-Information Technology Capital Services	1,53	1,72	2,48	2,94
Labor Services	3,02	1,70	3,39	2,18

Notes: Average annual percentage rates of growth.

[3] See Jorgenson and Stiroh (2000) for details on the estimates of outputs and inputs.

sources. The price of software services declined only 2.0 percent per year for 1995-9. Nonetheless, firms have been accumulating software very rapidly, with real capital services growing 16.3 percent per year. A possible explanation is that firms respond to computer price declines by investing in complementary inputs like software. However, a more plausible hypothesis is that the price indexes for software investment fail to hold performance constant, leading to an overstatement of inflation and an understatement of growth. This can be overcome only by extending constant performance price indexes to cover all of software.

Although the price decline for communications equipment during the period 1995-9 is comparable to that of software, investment in this equipment is more in line with prices. However, 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. High priority should be assigned to the development of constant performance price indexes for all of communications equipment.

Higher productivity in IT production raises TFP growth

Accounting for Growth

Growth accounting identifies the contributions of outputs as well as inputs to U.S. economic growth. The growth rate of the GDP is a weighted average of growth rates of the outputs of investment and consumption goods. 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 growth rates of capital and labor services and the *contribution* of each input is its weighted growth rate. Total factor productivity (TFP) is defined as output per unit of input.

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 capital-labor substitution. The second is improvement in *labor quality* and 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 two effects on growth. 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] Since labor is working with more and better equipment, 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.

Sources of Growth

Table 2 presents results of a growth accounting decomposition for the period 1948-99 and various sub-periods, following Jorgenson (2001). Economic

[4] Economics and Statistics Administration (2000), Table 3.1, p. 23, lists IT-producing industries.

Table 2

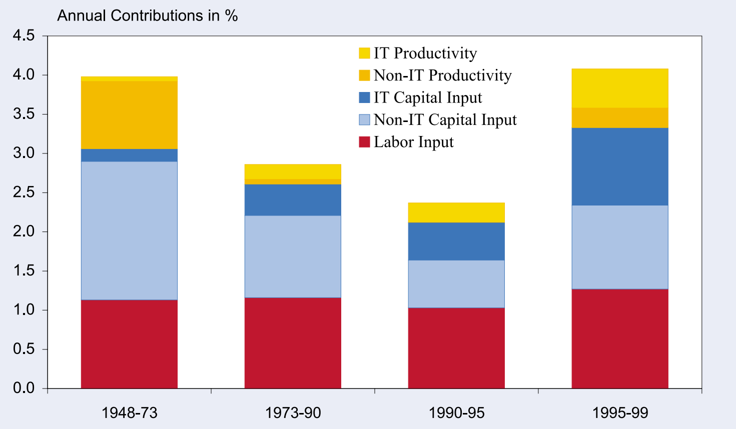
Sources of Gross Domestic Product Growth

	1948-99	1948-73	1973-90	1990-95	1995-99
	Outputs				
Gross Domestic Product	3,46	3,99	2,86	2,36	4,08
Contribution of Information Technology	0,40	0,20	0,46	0,57	1,18
Computers	0,12	0,04	0,16	0,18	0,36
Software	0,08	0,02	0,09	0,15	0,39
Communications Equipment	0,10	0,08	0,10	0,10	0,17
Information Technology Services	0,10	0,06	0,10	0,15	0,25
Contribution of Non-Information Technology	3,06	3,79	2,40	1,79	2,91
Contribution of Non-Information Technology Investment	0,72	1,06	0,34	0,23	0,83
Contribution of Non-Information Technology Consumption	2,34	2,73	2,06	1,56	2,08
	Inputs				
Gross Domestic Income	2,84	3,07	2,61	2,13	3,33
Contribution of Information Technology Capital Services	0,34	0,16	0,40	0,48	0,99
Computers	0,15	0,04	0,20	0,22	0,55
Software	0,07	0,02	0,08	0,16	0,29
Communications Equipment	0,11	0,10	0,12	0,10	0,14
Contribution of Non-Information Technology Capital Services	1,36	1,77	1,05	0,61	1,07
Contribution of Labor Services	1,14	1,13	1,16	1,03	1,27
Total Factor Productivity	0,61	0,92	0,25	0,24	0,75

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

Chart 3

SOURCES OF GROSS DOMESTIC PRODUCT GROWTH



Note: Input contributions are average annual rates of growth, weighted by average nominal income shares from Table 6. Productivity contributions are from Table 8.

growth is broken down by output and input categories, quantifying the contribution of information technology to investment and consumption outputs, as well as capital inputs. These estimates are based on computers, software, and communications equipment as distinct types of information technology.

Capital input contributes 1.70 percentage points to GDP growth for the entire period 1948 to 1999, labor input 1.14 percentage points, and TFP growth only 0.61 percentage points. Input growth is the source of nearly 82.3 percent of U.S. GDP growth of 3.46 percent per year over the past half century, while growth of output per unit of input or TFP has accounted for only 17.7 percent. Chart 3 depicts the relatively modest contributions of TFP in all sub-periods.

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 1950's, 1960's and early 1970's, the U.S. economy slowed markedly during 1973-90, with output growth falling from 3.99 percent for 1948–73 to 2.86 percent for 1973-90 and TFP growth declining from 0.92 percent to 0.25 percent. Growth in capital inputs also slowed from 4.64 percent to 3.57 percent.

Although the contribution of IT has increased steadily throughout the period 1948–99, there was a sharp and easily recognizable response to the acceleration in the IT price decline in 1995. Relative to the early 1990's, output growth increased by 1.72 percent in 1995-9. The contribution of IT production almost doubled, but still accounted for only 28.9 percent of the increased growth of output. More than 70 percent of the increased output growth can be attributed to non-IT products.

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. The rising importance of this investment has given additional weight to highly productive components of capital.

Between 1990-5 and 1995-9 the contribution of capital input jumped by 0.95 percentage points, the contribution of labor input rose by 0.24 percent, and TFP accelerated by 0.51 percent. The contribution of capital input reflects the investment boom of the late 1990's. 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 has boosted growth by nearly a full percentage point and IT accounts for more than half this increase.

The jump in the contribution of capital has boosted growth by nearly a half percentage point

After maintaining an average rate of 0.25 percent for the period 1973-90, TFP growth continued at 0.24 percent for 1990-5 and then vaulted to 0.75 percent per year for 1995-9. This increase in output per unit of input is an important source of growth in output of the U.S. economy as depicted in Chart 3. While TFP growth for 1995-9 is lower than the rate of 1948-73, the U.S. economy is definitely recuperating from the anemic productivity growth of the previous two decades.

The accelerating decline of IT prices signals faster productivity growth in IT-producing industries. In fact, these industries have been the source of most productivity growth throughout the 1990's. Before 1995 this was due to the decline of productivity growth elsewhere in the economy. The IT-producing industries have accounted for about half the surge in productivity growth since 1995, far greater than the 4.26 percent share of IT in the GDP. Faster growth is not limited to these industries and

Table 3

Sources of Average Labor Productivity Growth

	1948-99	1948-73	1973-90	1990-95	1995-99
Gross Domestic Product	3,46	3,99	2,86	2,36	4,08
Hours Worked	1,37	1,16	1,59	1,17	1,98
Average Labor Productivity	2,09	2,82	1,26	1,19	2,11
Contribution of Capital Deepening	1,13	1,45	0,79	0,64	1,24
Information Technology	0,30	0,15	0,35	0,43	0,89
Non-Information Technology	0,83	1,30	0,44	0,21	0,35
Contribution of Labor Quality	0,34	0,46	0,22	0,32	0,12
Total Factor Productivity	0,61	0,92	0,25	0,24	0,75
Information Technology	0,16	0,06	0,19	0,25	0,50
Non-Information Technology	0,45	0,86	0,06	-0,01	0,25
			Addendum		
Labor Input	1,95	1,95	1,97	1,70	2,18
Labor Quality	0,58	0,79	0,38	0,53	0,20
Capital Input	4,12	4,64	3,57	2,75	4,96
Capital Stock	3,37	4,21	2,74	1,82	2,73
Capital Quality	0,75	0,43	0,83	0,93	2,23

Notes: Average annual percentage rates of growth. Contributions are defined in Equation (3) of the text.

there is evidence of a productivity revival in the rest of the economy.

Average Labor Productivity

Output growth is the sum of growth in hours and average labor productivity. Table 3 reveals the well-known productivity slowdown of the 1970's and 1980's and depicts the acceleration in labor productivity growth in the late 1990's. The slowdown through 1990 reflects reduced capital deepening, declining labor quality growth, and decelerating growth in TFP. This contributed to the sluggish ALP growth revealed in Table 3 – 2.82 percent for 1948–73 and 1.26 percent for 1973–90.

Acceleration of average labor productivity was due to capital deepening and faster TFP growth

The growth of ALP slipped further during the early 1990's 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 produced 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.

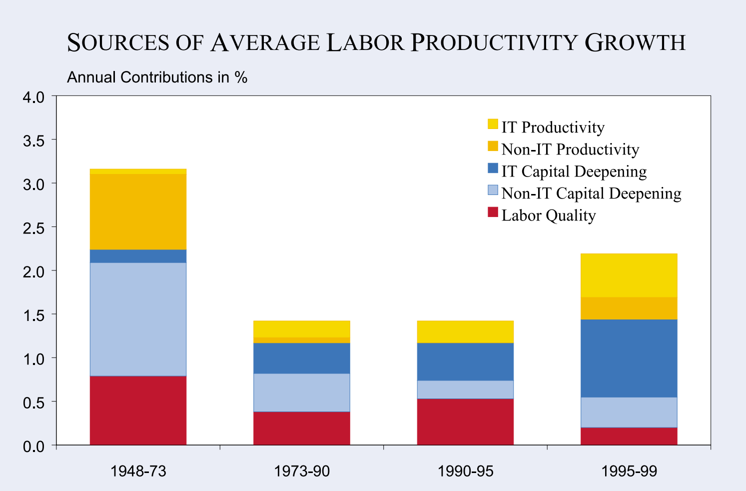
Accelerating output growth during 1995–99 reflects growth in labor hours and ALP almost equally. Growth in ALP rose 0.92 as more rapid capital deepening and growth in TFP offset slower improvement in labor quality. Growth in hours worked accelerated as unemployment fell to a 30-year low. Labor markets have tightened considerably, even as labor force participation rates increased.

Comparing 1990–95 to 1995–99, the rate of output growth jumped by 1.72 percent – due to an increase in hours worked of 0.81 percent and another increase in ALP growth of 0.92 percent. Chart 4 shows the acceleration in ALP growth is due to capital deepening as well as faster TFP growth. Capital deepening contributed 0.60 percentage points, offsetting a negative contribution of labor quality of 0.20 percent. The acceleration in TFP added 0.51 percentage points.

The difference between growth in capital input and capital stock is the *improvement in capital quality.* This represents the substitution towards assets with higher productivity. The growth of capital quality is slightly less than twenty percent of capital input growth for the period 1948–1995. However, improvements in capital jumped to 44.9 percent of total growth in capital input during the period 1995–99, reflecting very rapid restructuring of capital to take advantage of the sharp acceleration in the IT price decline.

The distinction between labor input and labor hours is analogous to the distinction between capital ser-

Chart 4



Note: Contributions are from Table 7.

vices 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. Table 3 presents estimates of labor input, hours worked, and labor quality.

As shown in Table 1, the growth rate of labor input accelerated to 2.18 percent for 1995–99 from 1.70 percent for 1990–95. This is primarily due to the growth of hours worked, which rose from 1.17 percent for 1990–95 to 1.98 percent for 1995–99, as labor force participation increased and unemployment rates plummeted. The growth of labor quality declined considerably in the late 1990's, dropping from 0.53 percent for 1990–95 to 0.20 percent for 1995–99. This slowdown captures well-known demographic trends in the composition of the work force, as well as exhaustion of the pool of available workers.

The acceleration in U.S. economic growth after 1995 is unmistakable and its relationship to information technology is now transparent. The most important contribution of IT is through faster growth of capital input, reflecting higher rates of investment. More rapid growth of output per unit of input also captures an important component of the contribution of IT. The issue that remains is whether these trends in economic growth are sustainable.

Long-term Outlook

Falling IT prices will continue to provide incentives for the substitution of IT for other productive inputs. The decline in IT prices will also serve as an indicator of ongoing productivity growth in IT-producing industries. However, 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 key assumption for long-term projections is that output and capital stock must grow at the same rate. Under this assumption the growth of output is the sum of the contributions of hours worked and labor quality, the contribution of capital quality growth, and the rate of TFP growth. So long as the two-year product cycle for semiconductors continues, the growth of TFP is likely to average 0.75 percent per year, the rate during 1995–99.

The long-term growth of hours worked and labor quality will average 1.5 percent per year. Growth of hours worked will slow considerably in order to remain in line with future growth of the labor force of 1.2 percent per year. Growth of labor quality will revive, modestly, to 0.3 percent per year, reflecting ongoing improvements in the productivity of individual workers. The overall contribution of labor input will be 0.9 percent per year, reflecting the growth rate of labor input of 1.5 percent per year and the proportion of labor input in the GDP of 59.3 percent in 1999.

The rapid substitution of IT assets for non-IT assets in response to declining IT prices is reflected in the contribution of capital quality. The growth of capital quality will continue at the recent rate of 2.2 percent per year, so long as the two-year product cycle for semiconductors persists. Weighting this growth rate by the proportion of capital input in the GDP of 40.7 percent in 1999 generates a future contribution of capital quality of 0.9 percent per year.

The two-year cycle for semiconductors is a key prerequisite for higher long term growth

The long-term growth rate of the U.S. economy is 3.4 percent per year, a drop of 0.7 percent per year from the 1995–99 average of 4.1 percent per year. Although the boom of the late 1990's was not sustainable, the growth prospects for the U.S. economy have improved considerably from the average of 2.9 percent per year from 1973–90 and 2.4 percent from 1990–1995. However, reversion to a three-year cycle for semiconductors could eliminate 0.25 percent per year from the TFP growth rate and 0.6 percent per year from the contribution of capital quality, resulting in a long-term growth rate of 2.9 percent per year, close to the 1973–90 average.

The economic forces that underlie the two-year product cycle for semiconductors reflect intensifying competition among semiconductor producers in the U.S. and around the world. Over the next decade persistence of this rapid rate of technological progress will require exploitation of new technologies. This is already generating a massive research and development effort that will strain the financial capacities of the semiconductor industry and its equipment suppliers.

Economics on Internet Time

I conclude by underlining some of the uncertainties that still surround the development and diffusion of information technology. Highest priority must be given to a better understanding of markets for semiconductors and, especially, the determinants of the product cycle. Improved data on the prices of telecommunications and software are essential for understanding the links between semiconductor technology and the growth of the American economy.

The semiconductor industry and the information technology industries are global in their scope with an elaborate international division of labor.[5] This poses important questions about the American growth resurgence. Where is the evidence of a new economy in other leading industrialized countries? Another conundrum is that several important participants – Korea, Malaysia, Singapore, and Taiwan – are "newly industrializing" economies. Developing countries like China and India are now beginning to play an important role in the industry.

The unexpected U.S. growth revival of the 1990's may alter economic perspectives

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 remains to be developed. Such a model would have to derive the demand for semiconductors from investment in information technology 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. For example, the Federal Reserve Board has recently undertaken a major research program on constant performance IT price indexes. In the meantime monetary policymakers must set policies without accurate measures of price change. Similarly, fiscal policy-makers confront on-going revisions of growth projections that drastically affect the outlook for future tax revenues and government spending.

The unanticipated American growth revival of the 1990's has considerable potential for altering economic perspectives. In fact, this is already foreshadowed in a steady stream of excellent books on the economics of information technology.[7] Economists are the fortunate beneficiaries of a new agenda for research that could refresh their thinking and revitalize their discipline.

References

Brynjolfsson, Erik, and Kahin, Brian, *Understanding the Digital Economy*, Cambridge, MA: The MIT Press, 2000.

Choi, Soon-Yong, and Whinston, Andrew B. *The Internet Economy: Technology and Practice*, Austin, TX: SmartEcon Publishing, 2000.

Christensen, Clayton M., *The Innovator's Dilemma*, Boston, Harvard Business School Press, 1997.

Economics and Statistics Administration, *Digital Economy 2000*, Washington, DC: U.S. Department of Commerce, June 2000.

Grove, Andrew S., *Only the Paranoid Survive: How to Exploit the Crisis Points that Challenge Every Company*, New York, Doubleday, 1996.

International Technology Roadmap for Semiconductors, *2000 Update*, Austin, TX: Sematech Corporation, December 2000.

Jorgenson, Dale W., "Information Technology and the U.S. Economy," *American Economic Review*, 91(1), March 2001, pp. 1–32.

Jorgenson, Dale W., and Stiroh, Kevin J., "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers on Economic Activity*, 2000b, 1, pp. 125–211.

Moulton, Brent R., "Improved Estimates of the National Income and Product Accounts for 1929-99: Results of the Comprehensive Revision," *Survey of Current Business*, 80(4), April 2000, pp. 11–7, 36-145.

Organisation for Economic Co-operation and Development, *A New Economy?* Paris: Organisation for Economic Co-operation and Development, 2000.

Shapiro, Carl, and Varian, Hal R., *Information Rules*, Boston: Harvard Business School Press, 1999.

[5] The role of information technology in U.S. economic growth is discussed by the Economics and Statistics Administration (2000); comparisons among OECD countries are given by the Organisation for Economic Co-operation and Development (2000).

[6] See, for example, Grove (1996) on the market for computers and semiconductors and Christensen (1997) on the market for storage devices.

[7] See, for example, Shapiro and Varian (1999), Brynjolfsson and Kahin (2000), and Choi and Whinston (2000).