INFORMATION TECHNOLOGY AND THE U.S. ECONOMY

Presidential Address to the

American Economic Association,

New Orleans, Louisiana, January 6, 2001

by

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December 13, 2000

The resurgence of the American economy since 1995 has outrun all but the most optimistic expectations. Economic forecasting models have been seriously off track and growth projections have been revised to reflect a more sanguine outlook only recently[1]. 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.

The starting point for the economic debate is the thesis that the 1990's are a mirror image of the 1970's, when an unfavorable series of "supply shocks" led to stagflation -- slower growth and higher inflation[2]. In this view, the development of information technology (IT) is one of a series of positive, but *temporary*, shocks. The competing perspective is that IT has produced a fundamental change in the U.S. economy, leading to a *permanent* improvement in growth prospects[3].

The relentless decline in the prices of information technology equipment has steadily enhanced the role of IT investment as a source of American economic growth. Productivity growth in IT-producing industries has gradually risen in importance and a productivity revival is now underway in the rest of the economy. Despite differences in methodology and data sources, a consensus is building that the remarkable behavior of IT prices provides the key to the surge in economic growth.

In the following section I show that the foundation for the American growth resurgence is the development and deployment of semiconductors. The decline in IT prices 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 of a wide variety of other products.

A substantial acceleration in the IT price decline occurred in 1995, triggered by a much sharper acceleration in the price decline of semiconductors in 1994. Although the decline in semiconductor prices has been projected to continue for at least another decade, the recent acceleration could be temporary. This can be traced to a shift in the product cycle for semiconductors from three years to two years that took place in 1995 as the consequence of intensifying competition in markets for semiconductor products.

In Section II I outline a framework for analyzing the role of information technology in the American growth resurgence. Constant quality price indexes separate the change in the 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.

The cost of capital is an essential concept for capturing the economic impact of information technology prices. Swiftly falling prices provide powerful economic incentives for the substitution of IT equipment for other forms of capital and for labor services. The rate of the IT price decline is a key component of the cost of capital, required for assessing the impacts of rapidly growing stocks of computers, communications equipment, and software.

In Section III I analyze the impact of the 1995 acceleration in the information technology price decline on U.S. economic growth. I introduce a production possibility frontier that encompasses substitutions between outputs of consumption and investment goods, as well as inputs of capital and labor services. This frontier treats IT equipment as part of investment goods output and the capital services from this equipment as a component of capital input.

Capital input has been the most important source of U.S. economic growth throughout the postwar period. More rapid substitution toward information technology has given much additional weight to components of capital input with higher marginal products. The vaulting contribution of capital input since 1995 has boosted growth by nearly a full percentage point. The contribution of IT accounts for more than half of this increase. Computers have been the predominant impetus to faster growth, but communications equipment and software have made important contributions as well.

The accelerated information technology price decline signals faster productivity growth in IT-producing industries. In fact, these industries have been the source of most of aggregate 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, but faster growth is not limited to these industries.

I conclude that the decline in IT prices will continue for some time. This will provide incentives for the ongoing substitution of IT for other productive inputs. Falling IT prices also serve as an indicator of rapid productivity growth in IT-producing industries. However, it would be premature to extrapolate the recent acceleration in productivity growth in these industries into the indefinite future, since this depends on the persistence of a two-year product cycle for semiconductors.

In Section IV I outline research opportunities created by the development and diffusion of information technology. A voluminous and rapidly expanding business literature is testimony to the massive impact of IT on firms and product markets. Highest priority must be given to a better understanding of the markets for semiconductors. Although several models of the market for semiconductors already exist, none explains the shift from a three-year to a two-year product cycle.

The dramatic effects of information technology on capital and labor markets have already generated a substantial and growing economic literature, but many important issues remain to be resolved. For capital markets the relationship between equity valuations and growth prospects merits much further study. For labor markets more research is needed on investment in information technology and substitution among different types of labor.

I. The Information Age.

The development and deployment of information technology is the foundation of the American growth resurgence. 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. The price decline has been transmitted to the prices of products that rely heavily on semiconductor technology, like computers and telecommunications equipment. This technology has also helped to reduce the cost of aircraft, automobiles, scientific instruments, and a host of other products.

Modern information technology begins with the invention of the *transistor*, a semiconductor device that acts as an electrical switch and encodes information in binary form. A binary digit or *bit* takes the values zero and one, corresponding to the off and on positions of a switch. The first transistor, made of the semiconductor germanium, was constructed at Bell Labs in 1947 and won the Nobel Prize in Physics in 1956 for the inventors -- John Bardeen, Walter Brattain, and William Shockley[4].

The next major milestone in information technology was the co-invention of the *integrated circuit* by Jack Kilby of Texas Instruments in 1958 and Robert Noyce of Fairchild Semiconductor in 1959. An integrated circuit consists of many, even millions, of transistors that store and manipulate data in binary form. Integrated circuits were originally developed for data storage and retrieval and semiconductor storage devices became known as ***memory chips***[5].

The first patent for the integrated circuit was granted to Noyce. This resulted in a decade of litigation over the intellectual property rights. The litigation and its outcome demonstrate the critical importance of intellectual property in the development of information technology. Kilby was awarded the Nobel Prize in Physics in 2000 for discovery of the integrated circuit; regrettably, Noyce died in 1990[6].

A. Moore's Law

In 1965 Gordon E. Moore, then Research Director at Fairchild Semiconductor, made a prescient observation, later known as ***Moore's Law***[7]. Plotting data on memory chips, he observed that each new chip contained roughly twice as many transistors as the previous chip and was released within 18-24 months of its predecessor. This implied exponential growth of chip capacity at 35-45 percent per year! Moore's prediction, made in the infancy of the semiconductor industry, has tracked chip capacity for thirty-five years. He recently extrapolated this trend for at least another decade[8].

In 1968 Moore and Noyce founded Intel Corporation to speed the commercialization of memory chips[9]. Integrated circuits gave rise to *microprocessors* with functions that can be programmed by software, known as *logic chips*. Intel's first general purpose microprocessor was developed for a calculator produced by Busicom, a Japanese firm. Intel retained the intellectual property rights and released the device commercially in 1971.

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

B. Semiconductor Prices.

Moore's Law captures the fact that successive generations of semiconductors are *faster* and *better*. The economics of semiconductors begins with the closely related observation that semiconductors have become *cheaper* at a truly staggering rate! Chart 1 gives semiconductor price indexes constructed by Bruce T. Grimm (1998) of the Bureau of Economic Analysis (BEA) and employed in the U.S. National Income and Product Accounts since 1996. These are divided between memory chips and logic chips. The underlying detail includes seven types of memory chips and two types of logic chips.

Between 1974 and 1996 prices of memory chips *decreased* by a factor of 27,270 times or at 40.9 percent per year, while the implicit deflator for the gross domestic product (GDP) *increased* by almost 2.7 times or 4.6 percent per year! Prices of logic chips, available for the shorter period 1985 to 1996, *decreased* by a factor of 1,938 or 54.1 percent per year, while the GDP deflator *increased* by 1.3 times or 2.6 percent per year! Semiconductor price declines closely parallel Moore's Law on the growth of chip capacity, setting semiconductors apart from other products.

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[10], prepared by a consortium of industry associations.

C. Constant Quality Price Indexes.

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

Ellen R. Dulberger (1993) of IBM introduced a "matched model" index for semiconductor prices. A matched model index combines price relatives for products with the same performance at different points of time. Dulberger presented constant quality price indexes based on index number formulas, including the *Fisher* (1922) *ideal index* used in the in the U.S. national accounts[11]. The Fisher index is the geometric average of the familiar Laspeyres and Paasche indexes.

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

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

Beginning in 1997, the Bureau of Labor Statistics (BLS) incorporated a matched model price index for semiconductors into the Producer Price Index (PPI) and since then the national accounts have relied on data from the PPI. Reflecting long-standing BLS policy, historical data were not revised backward. Semiconductor prices reported in the PPI prior to 1997 do not hold quality constant, failing to capture the rapid semiconductor price decline and the acceleration in 1994.

D. Computers.

The introduction of the Personal Computer (PC) by IBM in 1981 was a watershed event in the deployment of information technology. The sale of Intel's 8086-8088 microprocessor to IBM in 1978 for incorporation into the PC was a major business breakthrough for Intel[12]. In 1981 IBM licensed the MS-DOS operating system from the Microsoft Corporation, founded by Bill Gates and Paul Allen in 1975. The PC established an Intel/Microsoft relationship that has continued up to the present. In 1985 Microsoft released the first version of Windows, its signature operating system for the PC, giving rise to the Wintel (Windows-Intel) nomenclature for this ongoing collaboration.

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

Gregory C. Chow (1967) pioneered the use of hedonic techniques for constructing a constant quality index of computer prices in research conducted at IBM. Chow documented price declines at more than twenty percent per year during 1960-1965, providing an initial glimpse of the remarkable behavior of computer prices[13]. In 1985 the Bureau of Economic Analysis incorporated constant quality price indexes for computers and peripheral equipment constructed by Rosanne Cole, Y.C. Chen, Joan A. Barquin-Stolleman, Ellen R. Dulberger, Nurthan Helvacian, and James H. Hodge (1986) of IBM into the NIPA. Jack E. Triplett (1986) discussed the economic interpretation of these indexes, bringing the rapid decline of computer prices to the attention of a very broad audience.

The BEA-IBM constant quality price index for computers provoked a heated exchange between BEA and Edward F. Denison (1989), one of the founders of national accounting methodology in the 1950's and head of the national accounts at BEA from 1979 to 1982. Denison sharply attacked the BEA-IBM methodology and argued vigorously against the introduction of constant quality price indexes into the national accounts[14]. Allan Young (1989), then Director of BEA, reiterated BEA's rationale for introducing constant quality price indexes.

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

Chart 2 gives BEA's constant quality index of prices 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 parallels the acceleration in the semiconductor price decline that resulted from the changeover from a three-year product cycle to a two-year cycle in 1995.

E. Communications equipment and software.

Communications technology is crucial for the rapid development and diffusion of the Internet, perhaps the most striking manifestation of information technology in the American economy[15]. Kenneth Flamm (1989) was the first to compare the behavior of computer prices and the prices of communications equipment. He concluded that the communications equipment prices fell only a little more slowly than computer prices. Gordon (1990) compared Flamm's results with the official price indexes, revealing substantial bias in the official indexes.

Communications equipment is an important market for semiconductors, but constant quality price indexes cover only a portion of this equipment. Switching and terminal equipment rely heavily on semiconductor technology, so that product development reflects improvements in semiconductors. Grimm's (1997) constant quality price index for digital telephone switching equipment, given in Chart 3, was incorporated into the national accounts in 1996. The output of communications services in the NIPA also incorporates a constant quality price index for cellular phones.

Much communications investment takes the form of the transmission gear, connecting data, voice, and video terminals to switching equipment. Technologies such as fiber optics, microwave broadcasting, and communications satellites have progressed at rates that outrun even the dramatic pace of semiconductor development. An example is dense wavelength division multiplexing (DWDM), a technology that sends multiple signals over an optical fiber simultaneously. Installation of DWDM equipment, beginning in 1997, has doubled the transmission capacity of fiber optic cables every 6-12 months[16].

Both software and hardware are essential for information technology and this is reflected in the large volume of software expenditures. The eleventh comprehensive revision of the national accounts, released by BEA on October 27, 1999, re-classified computer software as investment[17]. Before this important advance, business expenditures on software were treated as current outlays, while personal and government expenditures were treated as purchases of nondurable goods. Software investment is growing rapidly and is now much more important than investment in computer hardware.

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

Parker and Grimm (2000) present a constant quality price index for prepackaged software, given in Chart 3. This combines a hedonic model of prices for business applications software and a matched model index for spreadsheet and word processing programs developed by Steven D. Oliner and Daniel D. Sichel (1994). Prepackaged software prices decline at more than ten percent per year over the period 1962-1998. Since 1998 the BEA has relied on a matched model price index for all prepackaged software from the PPI; prior to 1998 the PPI data do not hold quality constant.

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

F. Research Opportunities.

The official price indexes for computers and semiconductors provide the paradigm for economic measurement. These indexes capture the steady decline in IT prices and the recent acceleration in this decline. The official price indexes for central office switching equipment and prepackaged software also hold quality constant. BEA and BLS, the leading statistical agencies in price research, have carried out much of the best work in this area. However, a critical role has been played by price research at IBM, long the dominant firm in information technology[18].

It is important to emphasize that information technology is not limited to applications of semiconductors. Switching and terminal equipment for voice, data, and video communications have come to rely on semiconductor technology and the empirical evidence on prices of this equipment reflects this fact. Transmission gear employs technologies with rates of progress that far outstrip those of semiconductors. This important gap in our official price statistics can only be filled by constant quality price indexes for all types of communications equipment.

Investment in software is more important than investment in hardware. This was essentially invisible until BEA introduced new measures of prepackaged, custom, and own-account software investment into the national accounts in 1999. This is a crucial step in understanding the role of information technology in the American economy. Unfortunately, software prices are another statistical blind spot with only prices of prepackaged software adequately represented in the official system of price statistics. The daunting challenge that lies ahead is to construct constant quality price indexes for custom and own-account software.

II. The Role of Information Technology.

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. A methodology for analyzing economic growth must capture the substitution of IT outputs for other outputs of goods and services.

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. Sales of semiconductors to domestic manufacturers of IT products are precisely offset by purchases of semiconductors and are excluded from the GDP.

Constant quality price indexes, like those reviewed in the previous section, are a key component of the methodology for analyzing the American growth resurgence. Computer prices were incorporated into the NIPA in 1985 and are now part of the PPI as well. Much more recently, semiconductor prices have been included in the NIPA and the PPI. Unfortunately, evidence on the prices of communications equipment and software is seriously incomplete, so that the official price indexes are seriously misleading.

A. Output.

The output data in Table 1 are based on the most recent benchmark revision of the national accounts, updated through 1999[19]. The output concept is similar, but not identical, to the concept of gross domestic product used by the BEA. Both measures include final outputs purchased by businesses, governments, households, and the rest of the world. Unlike the BEA concept, the output measure in Table 1 also includes imputations for the service flows from durable goods, including IT products, employed in the household and government sectors.

The imputations for services of IT equipment are based on the cost of capital for IT described in more detail below. The cost of capital is multiplied by the nominal value of IT capital stock to obtain the imputed service flow from IT products. In the business sector this accrues as capital income to the firms that employ these products as inputs. In the household and government sectors the flow of capital income must be imputed. This same type of imputation is used for housing in the NIPA. The rental value of renter-occupied housing accrues to real estate firms as capital income, while the rental value of owner-occupied housing is imputed to households.

Current dollar GDP in Table 1 is $9.8 trillions in 1999, including imputations, and real output growth averaged 3.46 percent for the period 1948-99. These magnitudes can be compared to the current dollar value of $9.3 trillions in 1999 and the average real growth rate of 3.40 percent for period 1948-99 for the official GDP. Table 1 presents the current dollar value and price indexes of the GDP and IT output. This includes outputs of investment goods in the form of computers, software, communications equipment, and non-IT investment goods. It also includes outputs of non-IT consumption goods and services as well as imputed IT capital service flows from households and governments.

The most striking feature of the data in Table 1 is the rapid price decline for computer investment, 17.1 percent per year from 1959 to 1995. Since 1995 this decline has almost doubled to 32.1 percent per year. By contrast the relative price of software has been flat for much of the period and began to fall only in the late 1980's. The price of communications equipment behaves similarly to the software price, while the consumption of capital services from computers and software by households and governments shows price declines similar to computer investment.

The top panel of Table 2 summarizes the growth rates of prices and quantities for major output categories for 1990-5 and 1995-9. Business investments in computers, software, and communications equipment are the largest categories of IT spending. Households and governments have also spent sizable amounts on computers, software, communications equipment and the services of information technology. Chart 4 shows that the output of software is the largest IT category as a share of GDP, followed by the outputs of computers and communications equipment.

B. Capital Services.

This section presents capital estimates for the U.S. economy for the period 1948 to 1999[20]. These begin with BEA investment data; the perpetual inventory method generates estimates of capital stocks and these are aggregated, using service prices as weights. This approach, originated by Jorgenson and Zvi Griliches (1996), is based on the identification of service prices with marginal products of different types of capital. The service price estimates incorporate the cost of capital[21].

The cost of capital is an annualization factor that transforms the price of an asset into the price of the corresponding capital input[22]. This includes the nominal rate of return, the rate of depreciation, and the rate of capital loss due to declining prices. The cost of capital is an essential concept for the economics of information technology[23], due to the astonishing decline of IT prices given in Table 1.

The cost of capital is important in many areas of economics, especially in modeling producer behavior, productivity measurement, and the economics of taxation[24]. Many of the important issues in measuring the cost of capital have been debated for decades. The first of these is incorporation of the rate of decline of asset prices into the cost of capital. The assumption of perfect foresight or rational expectations quickly emerged as the most appropriate formulation and has been used in almost all applications of the cost of capital[25].

The second empirical issue is the measurement of economic depreciation. The stability of patterns of depreciation in the face of changes in tax policy and price shocks has been carefully documented. The depreciation rates presented by Jorgenson and Kevin J. Stiroh (2000b) summarize a large body of empirical research on the behavior of asset prices[26]. A third empirical issue is the description of the tax structure for capital income. This depends on the tax laws prevailing at each point of time. The resolution of these issues has cleared the way for detailed measurements of the cost of capital for all assets that appear in the national accounts, including information technology[27].

The definition of capital includes all tangible assets in the U.S. economy, equipment and structures, as well as consumers' and government durables, land, and inventories. The capital service flows from durable goods employed by households and governments enter measures of both output and input. A steadily rising proportion of these service flows are associated with investments in IT. Investments in IT by business, household, and government sectors must be included in the GDP, along with household and government IT capital services, in order to capture the full impact of IT on the U.S. economy.

Table 3 gives capital stocks from 1948 to 1999, as well as price indexes for total domestic tangible assets and IT assets -- computers, software, and communications equipment. The estimate of domestic tangible capital stock in Table 3 is $35.4 trillions in 1999, considerably greater than the $27.9 trillions in fixed capital estimated by Shelby W. Herman (2000) of BEA. The most important differences reflect the inclusion of inventories and land in Table 3.

Business IT investments, as well as purchases of computers, software, and communications equipment by households and governments, have grown spectacularly in recent years, but remain relatively small. The stocks of all IT assets combined account for only 4.35 percent of domestic tangible capital stock in 1999. Table 4 presents estimates of the flow of capital services and corresponding price indexes for 1948-99.

The difference between growth in capital services and capital stock is the *improvement in capital quality*. This represents the substitution towards assets with higher marginal products. The shift toward IT increases the quality of capital, since computers, software, and communications equipment have relatively high marginal products. Capital stock estimates fail to account for this increase in quality and substantially underestimate the impact of IT investment on growth.

The growth of capital quality is slightly less than twenty percent of capital input growth for the period 1948-1995. However, improvements in capital quality have increased steadily in relative importance. These improvements 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. Capital stock has become progressively less accurate as a measure of capital input and is now seriously deficient.

Chart 5 gives the IT capital service flows as a share of gross domestic income. The second panel of Table 2 summarizes the growth rates of prices and quantities of capital inputs for 1990-5 and 1995-9. Growth of IT capital services jumps from 11.51 percent per year in 1990-5 to 19.41 percent in 1995-9, while growth of non-IT capital services increases from 1.72 percent to 2.94 percent. This reverses the trend toward slower capital growth through 1995.

C. Labor Services.

This section presents estimates of labor input for the U.S. economy from 1948 to 1999. These incorporate individual data from the Censuses of Population for 1970, 1980, and 1990, as well as the annual Current Population Surveys. Constant quality indexes for the price and quantity of labor input account for the heterogeneity of the workforce across sex, employment class, age, and education levels. This follows the approach of Jorgenson, Frank M. Gollop, and

Barbara M. Fraumeni (1987). The estimates have been revised and updated by Mun S. Ho and Jorgenson (2000)[28].

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 substitution of workers with high marginal products for those with low marginal products. Table 5 presents estimates of labor input, hours worked, and labor quality.

The value of labor expenditures in Table 5 is $5.8 trillions in 1999, 59.3 percent of the value of output. This share accurately reflects the concept of gross domestic income, including imputations for the value of capital services in household and government sectors. As shown in Table 7, the growth rate of labor input accelerated to 2.18 percent for 1995-9 from 1.70 percent for 1990-5. This is primarily due to the growth of hours worked, which rose from 1.17 percent for 1990-5 to 1.98 percent for 1995-9, as labor force participation increased and unemployment rates plummeted.

The growth of labor quality has declined considerably in the late 1990's, dropping from 0.53 percent for 1990-5 to 0.20 percent for 1995-9. This slowdown captures well-known demographic trends in the composition of the work force, as well as exhaustion of the pool of available workers. Growth in hours worked does not capture these changes in labor quality growth and is a seriously misleading measure of labor input.

III. The American Growth Resurgence.

The American economy has undergone a remarkable resurgence since the mid-1990's with accelerating growth in output, labor productivity, and total factor productivity. The purpose of this section is to quantify the sources of growth for 1948-99 and various sub-periods. An important objective is to account for the sharp acceleration in the level of economic activity since 1995 and, in particular, to document the role of information technology.

The appropriate framework for analyzing the impact of information technology is the production possibility frontier, giving outputs of IT investment goods as well as inputs of IT capital services. An important advantage of this framework is that prices of IT outputs and inputs are linked through the price of IT capital services. This framework successfully captures the substitutions among outputs and inputs in response to the rapid deployment of IT. It also encompasses costs of adjustment, while allowing financial markets to be modeled independently.

As a consequence of the swift advance of information technology, a number of the most familiar concepts in growth economics have been superseded. The aggregate production function heads this list. Capital stock as a measure of capital input is now longer adequate to capture the rising importance of IT. This completely obscures the restructuring of capital input that is such an important wellspring of the growth resurgence. Finally, hours worked must be replaced as a measure of labor input.

A. Production Possibility Frontier.

The *production possibility frontier* describes efficient combinations of outputs and inputs for the economy as a whole[29]. Aggregate output Y consists of outputs of investment goods and consumption goods. These outputs are produced from aggregate input X, consisting of capital services and labor services. Productivity is a "Hicks-neutral" augmentation of aggregate input.

The production possibility frontier takes the form:

$$(1) \quad Y(I_n, I_c, I_s, I_t, C_n, C_c) = A \cdot X(K_n, K_c, K_s, K_t, L),$$

where the outputs include non-IT investment goods I_n and investments in computers I_c, software I_s, and communications equipment I_t, as well as non-IT consumption goods and services C_n and IT capital services to households and governments C_c. Inputs include non-IT capital services K_n and the services of computers K_c, software K_s, and telecommunications equipment K_t , as well as labor input L.[30] ***Total factor productivity*** (TFP) is denoted by A.

The most important advantage of the production possibility frontier is the explicit role that it provides for constant quality prices of IT products. These are used as deflators for nominal expenditures on IT investments to obtain the quantities of IT outputs. Investments in IT are cumulated into stocks of IT capital. The flow of IT capital services is an aggregate of these stocks with service prices as weights. Similarly, constant quality prices of IT capital services are used in deflating the nominal values of consumption of these services.

Another important advantage of the production possibility frontier is the incorporation of costs of adjustment. For example, an increase in the output of IT investment goods requires foregoing part of the output of consumption goods and non-IT investment goods, so that adjusting the rate of investment in IT is costly. However, costs of adjustment are external to the producing unit and are fully reflected in IT prices. These prices incorporate forward-looking expectations of the future prices of IT capital services.

B. Aggregate Production Function.

The aggregate production function employed by Robert M. Solow (1957, 1960) and, more recently, by Jeremy Greenwood, Zvi Hercowitz, and Per Krusell (1997, 2000), Hercowitz (1998), and Arnold C. Harberger (1998) is a competing methodology. The production function gives a single output as a function of capital and labor inputs. There is no role for separate prices of investment and consumption goods and, hence, no place for constant quality IT price indexes for outputs of IT investment goods.

Greenwood, Hercowitz, and Krusell employ a price index for consumption to deflate the output of all investment goods, including information technology. Confronted by the fact that constant quality prices of investment goods differ from consumption goods prices, they borrow the concept of ***embodiment*** from Solow (1960) in order to convert investment goods output into an appropriate form for measuring capital stock[31]. Investment has two prices, one used in the measuring output and the other used in measuring capital stock. This inconsistency can be removed by simply distinguishing between outputs of consumption and investment goods, as in the national accounts and Equation (1). The concept of embodiment can then be dropped.

Perhaps inadvertently, Greenwood, Hercowitz, and Krussell have revisited the controversy accompanying the introduction of a constant quality price index for computers into the national accounts. They have revived Denison's (1993) proposal to use a consumption price index to deflate investment in the NIPA. Denison found this appealing as a means of avoiding the introduction of constant quality price indexes for computers. Denison's approach leads to a serious underestimate of GDP growth and an overestimate of inflation.

Another limitation of the aggregate production function is that it fails to incorporate costs of adjustment. Robert E. Lucas, Jr., (1967) presented a production model with internal costs of adjustment. Fumio Hayashi (2000) shows how to identify these adjustment costs from James Tobin's (1969) Q-ratio, the ratio of the stock market value of the producing unit to the market value of the unit's assets. Implementation of this approach requires simultaneous modeling of production and asset valuation. If costs of adjustment are external, as in the production possibility frontier (1), asset valuation can be modeled separately from production[32].

C. Sources of Growth.

Under the assumption that product and factor markets are competitive producer equilibrium implies that the share-weighted growth of outputs is the sum of the share-weighted growth of inputs and growth in total factor productivity:

$$(2)\quad \overline{w}_{I,n}\Delta \ln I_n + \overline{w}_{I,c}\Delta I_c + \overline{w}_{I,s}\Delta I_s + \overline{w}_{I,t}\Delta I_t + \overline{w}_{C,n}C_n + \overline{w}_{C,c}\Delta \ln C_c =$$
$$\overline{v}_{K,n}\Delta \ln K_n + \overline{v}_{K,c}\Delta \ln K_c + \overline{v}_{K,s}\Delta \ln K_s + \overline{v}_{K,t}\Delta \ln K_t + \overline{v}_L \Delta \ln L + \Delta \ln A$$

where $\overline{w}$ and $\overline{v}$ denote average value shares. The shares of outputs and inputs add to one under the additional assumption of constant returns, $\overline{w}_{I,n} + \overline{w}_{I,c} + \overline{w}_{I,s} + \overline{w}_{I,t} + \overline{w}_{C,n} + \overline{w}_{C,c} = \overline{v}_{K,n} + \overline{v}_{K,c} + \overline{v}_{K,s} + \overline{v}_{K,t} + \overline{v}_L = 1$.

Equation (2) makes it possible to identify the contributions of outputs as well as inputs to U.S. economic growth. The growth rate of output is a weighted average of growth rates of investment and consumption goods outputs. The *contribution* of each output is its weighted growth rate. 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. The *contribution* of TFP, the growth rate of the augmentation factor A in Equation (2), is the difference between growth rates of output and input.

Table 6 presents results of a growth accounting decomposition, based on Equation (2), for the period 1948-99 and various sub-periods, following Jorgenson and Stiroh (1999, 2000b). Economic 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 identify computers, software, and communications equipment as distinct types of information technology.

Rearranging Equation (2), the results can be presented in terms of *average labor productivity* (ALP), defined as $y = Y/H$, the ratio of output Y to hours worked H, and $k = K/H$ is the ratio of capital services K to hours worked:

$$(3)\quad \Delta \ln y = \overline{v}_K \Delta \ln k + \overline{v}_L \left(\Delta \ln L - \Delta \ln H\right) + \Delta \ln A .$$

Equation (3) allocates ALP growth among three sources. The first is *capital deepening*, the growth in capital input per hour worked, and reflects the capital-labor substitution. The second is *improvement in labor quality* and captures the rising proportion of hours by workers with higher marginal products. The third is *TFP growth*, which contributes point-for-point to ALP growth.

D. Contributions of IT Investment.

Chart 5 depicts the rapid increase in the importance of IT services, reflecting the accelerating pace of IT price declines. In 1995-9 the capital service price for computers fell 24.81 percent per year, compared to an increase of 36.36 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 sources. The price of software services has declined only 2.04 percent per year for 1995-9. Nonetheless, firms have been accumulating software very rapidly, with real capital services growing 16.30 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 explanation is that the price indexes used to deflate software investment fail to hold quality constant. This leads to an overstatement of inflation and an understatement of growth.

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, prices of communications equipment also fail to hold quality constant. The technology of switching equipment, for example, is similar to that of computers; investment in this category is deflated by a constant-quality price index developed by BEA. Conventional price deflators are employed for transmission gear, such as fiber-optic cables. This leads to an underestimate of the growth rates of investment, capital stock, capital services, and the GDP, as well as an overestimate of the rate of inflation.

Charts 6 and 7 highlight the rising contributions IT outputs to U.S. economic growth. Chart 6 shows the breakdown between IT and non-IT outputs for sub-periods from 1948 to 1999, while Chart 7 decomposes the contribution of IT into its components. Although the importance of IT has steadily increased, Chart 6 shows that the recent investment and consumption surge nearly doubled the output contribution of IT. Chart 7 shows that computer investment is the largest single IT contributor in the late 1990's, but that investments in software and communications equipment are becoming increasingly important.

Charts 8 and 9 present a similar decomposition of IT inputs into production. The contribution of these inputs is rising even more dramatically. Chart 8 shows that the contribution of IT now accounts for more than 48.1 percent of the total contribution of capital input. Chart 9 shows that computer hardware is the largest IT contributor on the input side, reflecting the growing share and accelerating growth rate of computer investment in the late 1990's.

Private business investment predominates in the output of IT, as shown by Jorgenson and Stiroh (1999, 2000b)[33]. Household purchases of IT equipment and services are next in importance. Government purchases of IT equipment and services, as well as net exports of IT products, must be included in order to provide a complete picture. Firms, consumers, governments, and purchasers of U.S. exports are responding to relative price changes, increasing the contributions of computers, software, and communications equipment.

Table 2 shows that the price of computer investment fell by more than 32 percent per year, the price of software 2.4 percent, and the price of communications equipment 2.9 percent, and the price of IT services 11.8 percent during the period 1995-9, while non-IT prices rose 2.2 percent. In response to these price changes, firms, households, and governments have accumulated computers, software, and communications equipment much more rapidly than other forms of capital.

E. Total Factor Productivity.

The price or "dual" approach to productivity measurement makes it possible to identify the role of IT production as a source of productivity growth at the industry level[34]. The rate of productivity growth is measured as the decline in the price of output, plus a weighted average of the growth rates of input prices with value shares of the inputs as weights. For the computer industry this expression is dominated by two terms: the decline in the price of computers and the contribution of the price of semiconductors. For the semiconductor industry the expression is dominated by the decline in the price of semiconductors[35].

Jorgenson, Gollop, and Fraumeni (1987) have employed Evsey Domar's (1961) model to trace aggregate productivity growth to its sources at the level of individual industries[36]. More recently, Harberger (1998), William Gullickson and Michael J. Harper (1999) and Jorgenson and Stiroh (2000a, 2000b) have used the model for similar purposes. Productivity growth for each industry is weighted by the ratio of the gross output of the industry to GDP to estimate the industry contribution to aggregate TFP growth.

If semiconductor output were only used to produce computers, then its contribution to computer industry productivity growth, weighted by computer industry output, would precisely cancel its independent contribution to aggregate TFP growth. This is the ratio of the value of semiconductor output to GDP, multiplied by the rate of semiconductor price decline. In fact, semiconductors are used to produce telecommunications equipment and many other products. However, the value of semiconductor output is dominated by inputs into IT production.

The Domar aggregation formula can be approximated by expressing the declines in prices of computers, communications equipment, and software relative to the price of gross domestic income, an aggregate of the prices of capital and labor services. The rates of relative IT price decline are weighted by ratios of the outputs of IT products to the GDP. Table 8 reports details of this TFP decomposition for 1990-5 and 1995-9; the IT and non-IT contributions are presented in Chart 10. The IT products contribute 0.50 percentage points to TFP growth for 1995-9, compared to 0.25 percentage points for 1990-5. This reflects the accelerating decline in relative price changes resulting from shortening the product cycle for semiconductors.

F. Output Growth.

This section presents the sources of GDP growth for the entire period 1948 to 1999. Capital services contribute 1.70 percentage points, labor services 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. growth over the past half century, while TFP has accounted for 17.7 percent. Chart 11 shows the relatively modest contributions of TFP in all sub-periods.

More than three-quarters of the contribution of capital reflects the accumulation of capital stock, while improvement in the quality of capital accounts for about one-quarter. Similarly, increased labor hours account for 80 percent of labor’s contribution; the remainder is due to improvements in labor quality. Substitutions among capital and labor inputs in response to price changes are essential components of the sources of economic 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 1950's, 1960's and early 1970's, the U.S. economy slowed markedly through 1990, with output growth falling from 3.99 percent to 2.86 percent and TFP growth declining from 0.92 percent to 0.25 percent. Growth in capital inputs also slowed from 4.64 percent for 1948-73 to 3.57 percent for 1973-90. This contributed to sluggish ALP growth -- 2.82 percent for 1948-73 and 1.26 percent for 1973-90.

Relative to the early 1990's, output growth increased by 1.72 percent in 1995-9. The contribution of IT production almost doubled, relative to 1990-5, but still accounted for only 28.9 percent of the increased growth of output. Although the contribution of IT has increased steadily throughout the period 1948-99, there has been a sharp response to the acceleration in the IT price decline in 1995. Nonetheless, more than 70 percent of the increased output growth can be attributed to non-IT products.

Between 1990-5 and 1995-9 the contribution of capital input jumped by 0.95 percentage points, the contribution of labor input rose by only 0.24 percent, and TFP accelerated by 0.51 percent. 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.[37]

The contribution of capital input reflects the investment boom of the late 1990's as businesses, households, and governments poured resources into plant and equipment, especially computers, software, and communications equipment. The contribution of capital, predominantly IT, is considerably more important than the contribution of labor. The contribution of IT capital services has grown steadily throughout the period 1948-99, but Chart 9 reflects the impact of the accelerating decline in IT prices.

After maintaining an average rate of 0.25 percent for the period 1973-90, TFP growth fell to 0.24 percent for 1990-5 and then vaulted to 0.75 percent per year for 1995-9. This is a major source of growth in output and ALP for the U.S. economy (Charts 11 and 12). While TFP growth for 1995-9 is lower than the rate of 1948-73, the U.S. economy is recuperating from the anemic productivity growth of the past two decades. Although only half of the acceleration in TFP from 1990-5 to 1995-9 can be attributed to IT production, this is far greater than the 4.26 percent share of IT in the GDP.

G. Average Labor Productivity.

Output growth is the sum of growth in hours and average labor productivity. Table 7 shows the breakdown between growth in hours and ALP for the same periods as in Table 6. For the period 1948-99, ALP growth predominated in output growth, increasing just over 2 percent per year for 1948-99, while hours increased about 1.4 percent per year. As shown in Equation (3), ALP growth depends on capital deepening, a labor quality effect, and TFP growth.

Chart 12 reveals the well-known productivity slowdown of the 1970's and 1980's, emphasizing 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. 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 1990-5 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 1995-9 reflects growth in labor hours and ALP almost equally[38]. Comparing 1990-5 to 1995-9, 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 12 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.

H. Research Opportunities.

The use of computers, software, and communications equipment must be carefully distinguished from the production of IT[39]. 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. Since labor is working with more and better equipment, this increases ALP through capital deepening. If the contributions to aggregate output are captured by capital deepening, aggregate TFP growth is unaffected[40]. Increasing deployment of IT affects TFP growth only if there are spillovers from IT-producing industries to IT-using industries.

Top priority must be given to identifying the impact of investment in IT at the industry level. Stiroh (1998) has shown that this is concentrated in a small number of IT-using industries, while Stiroh (2000) shows that aggregate ALP growth can be attributed to productivity growth in IT-producing and IT-using industries. The next priority is to trace the increase in aggregate TFP growth to its sources in individual industries. Jorgenson and Stiroh (2000a, 2000b) present the appropriate methodology and preliminary results.

IV. Economics on Internet Time.

The steadily rising importance of information technology has created new research opportunities in all areas of economics. Economic historians, led by Alfred D. Chandler (2000) and Paul A. David (2000)[41], have placed the information age in historical context. The Solow (1987) Paradox, that we see computers everywhere but in the productivity statistics[42], has provided a point of departure. Since computers have now left an indelible imprint on the productivity statistics, the remaining issue is whether the breathtaking speed of technological change in semiconductors differentiates this resurgence from previous periods of rapid growth?

Capital and labor markets have been severely impacted by information technology. Enormous uncertainty surrounds the relationship between equity valuations and future growth prospects of the American economy[43]. One theory attributes rising valuations of equities since the growth acceleration began in 1995 to the accumulation of intangible assets, such as intellectual property and organizational capital. An alternative theory treats the high valuations of technology stocks as a bubble that burst during the year 2000.

The behavior of labor markets also poses important puzzles. Widening wage differentials between workers with more and less education has been attributed to computerization of the workplace. A possible explanation could be that high-skilled workers are complementary to IT, while low-skilled workers are substitutable. An alternative explanation is that technical change associated with IT is skill-biased and increases the wages of high-skilled workers relative to low-skilled workers[44].

Finally, information technology is altering product markets and business organizations, as attested by the large and growing business literature[45], but a fully satisfactory model of the semiconductor industry remains to be developed[46]. Such a model would derive the demand for semiconductors from investment in information technology in response to rapidly falling IT prices. An important objective is to determine the product cycle for successive generations of new semiconductors endogenously.

The semiconductor industry and the information technology industries are global in their scope with an elaborate international division of labor[47]. This poses important questions about the American growth resurgence. Where is the evidence of a new economy in other leading industrialized countries? An important explanation is the absence of constant quality price indexes for semiconductors and information technology in national accounting systems outside the U.S.[48]. Another conundrum is that several important participants -- Korea, Malaysia, Singapore, and Taiwan -- are "newly industrializing" economies. What does this portend for developing countries like China and India?

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. In the mean time monetary policy-makers 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 stagflation of the 1970's greatly undermined the Keynesian Revolution, leading to a New Classical Counter-revolution led by Lucas (1981) that has transformed macroeconomics. The unanticipated American growth revival of the 1990's has similar potential for altering economic perspectives. In fact, this is already foreshadowed in a steady stream of excellent books on the economics of information technology[49]. We are the fortunate beneficiaries of a new agenda for economic research that could refresh our thinking and revitalize our discipline.

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*Department of Economics, Harvard University, 122 Littauer Center, Cambridge, MA 02138-3001. I am indebted to the Program on Technology and Economic Policy at Harvard University provided financial support. I am also indebted to Kevin J. Stiroh for our joint research and his helpful comments, Jon Samuels for excellent research assistance, Mun S. Ho for the labor data, as well as useful comments. J. Steven Landefeld, Clinton McCully, and David Wasshausen of the Bureau of Economic Analysis provided valuable data on information technology. Colleagues far too numerous to mention have contributed useful suggestions and advice. I am grateful to all of them but retain sole responsibility for any remaining deficiencies.

[1] See Congressional Budget Office (2000) on official forecasts and Economics and Statistics Administration (2000), p. 60, on private forecasts.

[2] Gordon (1998, 2000); Bosworth and Triplett (2000).

[3] Greenspan (2000).

[4] On Bardeen, Brattain, and Shockley, see:

http://www.nobel.se/physics/laureates/1956/.

[5] Petzold (2000) provides a general reference on computers and software.

[6] On Kilby, see: http://www.nobel.se/physics/laureates/2000/. On Noyce, see: Wolfe (2000), pp. 17-65.

[7] Moore (1965). Ruttan (2001), pp.316-367, provides a general reference on the economics of semiconductors and computers. On semiconductor technology, see: http://euler.berkeley.edu/~esrc/csm.

[8] Moore (1997).

[9] Moore (1996).

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

[11] See Landefeld and Parker (1997).

[12] See Moore (1996).

[13] Further details are given by Berndt (1991), pp. 102-149.

[14] Denison cited his 1957 paper, "Theoretical Aspects of Quality Change, Capital Consumption, and Net Capital Formation," as the definitive statement of the traditional BEA position.

[15] A general reference on the Internet is Choi and Whinston (2000). On Internet indicators see: http://www.internetindicators.com/.

[16] Rashad (2000) characterizes this as the "demise" of Moore's Law. Hecht (1999) describes DWDM technology and provides a general reference on fiber optics.

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

[18] See Chandler (2000), Table 1.1, p. 26.

[19] See Jorgenson and Stiroh (2000b), Appendix A, for details on the estimates of output.

[20] See Jorgenson and Stiroh (2000b), Appendix B, for details on the estimates of capital input.

[21]Jorgenson (2000) presents a model of capital as a factor of production. BLS (1983) describes the version of this model employed in the official productivity statistics. For a recent update, see: http://www.bls.gov/news.release/prd3.nr0.htm. Hulten (2001) surveys the literature.

[22] Jorgenson and Yun (1991), p. 7.

[23] Jorgenson and Stiroh (1995), pp. 300-303.

[24] Lau (2000) surveys applications of the cost of capital.

[25] See, for example, Jorgenson, Gollop, and Fraumeni (1987), pp. 40-9, and Jorgenson and Griliches (1996).

[26] Jorgenson and Stiroh (2000b), Table B4, pp. 196-7 give the depreciation rates employed in this study. Fraumeni (1997) describes depreciation rates used in the NIPA. Jorgenson (2000) surveys empirical studies of depreciation.

[27] See Jorgenson and Yun (2001). Diewert and Lawrence (2000) survey measures of the price and quantity of capital input.

[28]See Jorgenson and Stiroh (2000b), Appendix C, for details on the estimates of labor input. Gollop (2000) discusses the measurement of labor quality.

[29] The production possibility frontier was introduced into productivity measurement by Jorgenson (1996), pp. 27-28.

[30] Services of durable goods to governments and households are included in both inputs and outputs.

[31] Whelan (1999) also employs Solow's concept of embodiment.

[32] See, for example, Campbell and Shiller (1998).

[33] Bosworth and Triplett (2000) compare the results of Jorgenson and Stiroh (2000b) with those of Oliner and Sichel (2000).

[34] The dual approach is presented by Jorgenson, Gollop, and Fraumeni (1987), pp.

53-63.

[35] Dulberger (1993), Triplett (1996), and Oliner and Sichel (2000) present models of the relationships between computer and semiconductor industries. These are special cases of the Domar (1961) aggregation scheme.

[36] See Jorgenson, Gollop, and Fraumeni (1987), pp. 63-66, 301-322.

[37] Katz and Krueger (1999) analyze the recent performance of the U.S. labor market.

[38] Stiroh (2000) shows that ALP growth is concentrated in IT-producing and IT-using industries.

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

[40] Baily and Gordon (1988).

[41] See also: David (1990) and Gordon (2000).

[42] Griliches (1994), Brynjolfsson and Yang (1996), and Triplett (1999) discuss the Solow Paradox.

[43] Campbell and Shiller (1998) and Shiller (2000) discuss equity valuations and growth prospects. Kiley (1999), Brynjolfsson and Hitt (2000), and Hall (2000), present models of investment with internal costs of adjustment.

[44] Acemoglu (2000) and Katz (2000) survey the literature on labor markets and technological change.

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

[46] Irwin and Klenow (1994), Flamm (1996), pp. 305-424, and Helpman and Trajtenberg (1998), pp. 111-119, present models of the semiconductor industry.

[47] 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).

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[48] The measurement gap between the U.S. and other OECD countries was first identified by Wykoff (1995). Schreyer (2000) has taken the initial steps to fill this gap.

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