Raising the Speed Limit: U.S. Economic Growth in the Information Age

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Dale W. Jorgenson and Kevin J. Stiroh

2.1 Introduction

THE CONTINUED STRENGTH AND VITALITY of the U.S. economy continues to astonish economic forecasters.[1] A consensus is now emerging that something fundamental has changed, with "new economy" proponents pointing to information technology as the causal factor behind the strong performance of the U.S. economy. In this view, technology is profoundly altering the nature of business, leading to permanently higher productivity growth throughout the economy. Sceptics argue that the recent success reflects a series of favourable, but temporary, shocks. This argument is buttressed by the perception that the U.S. economy behaves rather differently than envisioned by new economy advocates.[2]

While productivity growth, capital accumulation, and the impact of technology were topics once reserved for academic debates, the recent strong performance of the U.S. economy has moved them into popular discussion. The purpose of this paper is to employ well-tested and familiar methods to analyze important new information made available by the recent benchmark revision of the U.S. National Income and Product Accounts (NIPA). We document the case for raising the speed limit — for upward revision of intermediate-term projections of future growth to reflect the latest data and trends.

The late 1990s have been exceptional in comparison with the growth experience of the U.S. economy over the past quarter century. While growth rates in the 1990s have not yet returned to those of the golden age of the U.S. economy in the 1960s, the data nonetheless clearly reveal a remarkable transformation of economic activity. Rapid declines in the prices of computers and semiconductors are well known and carefully documented, and evidence is accumulating that similar declines are taking place in the prices of software and communications equipment. Unfortunately, the empirical record is seriously incomplete, so much remains to be done before definitive quantitative assessments can be made about the complete role of these high-tech assets.

Despite the limitations of the available data, the mechanisms underlying the structural transformation of the U.S. economy are readily apparent. As an illustration, consider the increasing role that computer hardware plays as a source of economic growth.[3] For the period 1959 to 1973, computer inputs contributed less than one-tenth of one percent to U.S. economic growth. Since 1973, however, the price of computers has fallen at historically unprecedented rates and firms and households have followed a basic principle of economics — they have substituted towards relatively cheaper inputs. Since 1995, the price decline of computers has accelerated, reaching nearly 28 percent per year from 1995 to 1998. In response, investment in computers has exploded and the contribution of computers to growth has increased more than five-fold to 0.46 percentage points per year in the late 1990s.[4] Software and communications equipment, two other information technology assets, contributed an additional 0.30 percentage points per year for 1995-98. Preliminary estimates through 1999 reveal further increases in these contributions for all three high-tech assets.

Next, consider the acceleration of average labour productivity (ALP) growth in the 1990s. After a 20-year slowdown dating from the early 1970s, ALP grew 2.4 percent per year for 1995-98, more than a percentage point faster than during 1990-95.[5] A detailed decomposition shows that capital deepening, the direct consequence of price-induced substitution and rapid investment, added 0.49 percentage points to ALP growth. Faster total factor productivity (TFP) growth contributed an additional 0.63 percentage points, largely reflecting technical change in the production of computers and the resulting acceleration in their price decline. Slowing labour quality growth retarded ALP growth by 0.12 percentage points, relative to the early 1990s, a consequence of the exhaustion of the pool of available workers.

Focusing more specifically on TFP growth, it recorded an anaemic 0.34 percent per year for 1973-95, but accelerated to 0.99 percent during 1995-98. After more than twenty years of sluggish TFP growth, four of the last five years have seen growth rates near 1 percent. It could be argued that this represents a new paradigm. According to this view, the diffusion of information technology improves business practices, generates spillovers, and raises productivity throughout the economy. If this trend is sustainable, it could revive the optimistic expectations of the 1960s and overcome the pessimism of *The Age of Diminished Expectations*, the title of Krugman's (1990) influential book.

A closer look at the data, however, shows that gains in TFP growth can be traced in substantial part to information technology industries, which produce computers, semi-conductors, and other high-tech gear. The evidence is equally clear that computer-using industries like finance, insurance, and real estate (FIRE) and services have continued to lag in productivity growth. Reconciliation of massive high-tech investment and relatively slow productivity growth in service industries remains an important task for proponents of the new economy vision.[6]

What does this imply for the future? The sustainability of growth in labour productivity is the key issue for future growth projections. For some purposes, the distinctions among capital accumulation and growth in labour quality and TFP may not matter, so long as ALP growth can be expected to continue. It is sustainable labour productivity gains, after all, that ultimately drive long-run growth and raise living standards.

In this respect, the recent experience provides grounds for caution, since much depends on productivity gains in high-tech industries. Ongoing technological gains in these industries have been a direct source of improvement in TFP growth, as well as an indirect source of more rapid capital deepening. The sustainability of growth, therefore, hinges critically on the pace of technological progress in these industries. As measured by relative price changes, progress has accelerated recently, as computer prices fell 28 percent per year during 1995-98 compared to 15 percent during 1990-95. Of course, there is no guarantee of continued productivity gains and price declines of this magnitude. Nonetheless, as long as high-tech industries maintain the ability to innovate and improve their productivity at rates comparable even to their long-term averages, relative prices will fall and the virtuous circle of an investment-led expansion will continue.[7]

Finally, we argue that rewards from new technology accrue to the direct participants; first, to the innovating industries producing high-tech assets and, second, to the industries that restructure to implement the latest information technology. There is no evidence of spillovers from production of information technology to the industries that use this technology. Indeed, many of the industries that use information technology most intensively, like FIRE and services, show high rates of substitution of information technology for other inputs and relatively low rates of productivity growth. In part, this may reflect problems in measuring the output of these industries, but the empirical record provides little support for the "new economy" picture of spillovers cascading from information technology producers onto users of this technology.[8]

The chapter is organized as follows. Section 2 describes our methodology for quantifying the sources of U.S. economic growth. We present results for the period 1959-1998, and focus on the "new economy" era of the late 1990s. Section 3 explores the implications of the recent experience for future growth, comparing our results to recent estimates produced by the Congressional Budget Office (CBO), the Council of Economic Advisors (CEA), and the Office of Management and Budget (OMB). Section 4 moves beyond the aggregate data and quantifies the productivity growth at the industry level. Using methodology introduced by Domar (1961), we consider the impact of information technology on aggregate productivity. Section 5 concludes.

2.2 The Recent U.S. Growth Experience

THE U.S. ECONOMY HAS UNDERGONE a remarkable transformation in recent years with growth in output, labour productivity, and total factor productivity all accelerating since the mid-1990s. This resurgence of growth has led to a widening debate about sources of economic growth and changes in the structure of the economy. "New economy" proponents trace the changes to developments in information technology, especially the rapid commercialization of the Internet, that are fundamentally changing economic activity. "Old economy" advocates focus on the lacklustre performance during the first half of the 1990s, the increase in labour force participation and rapid decline in unemployment since 1993, and the recent investment boom.

Our objective is to quantify the sources of the recent surge in U.S. economic growth, using new information made available by the benchmark revision of the U.S. National Income and Product Accounts (NIPA) released in October 1999 (BEA, 1999). We then consider the implications of our results for intermediate-term projections of U.S. economic growth. We give special attention to the rapid escalation of growth rates in the official projections, such as those estimated by the Congressional Budget Office and the Council of Economic Advisers. The CBO projections are particularly suitable for our purposes, since they are widely disseminated, well documented, and represent the "best practice." We do not focus on the issue of inflation and do not comment on potential implications for monetary policy.

2.2.1 Sources of Economic Growth

Our methodology is based on the production possibility frontier introduced by Jorgenson (1966) and employed by Jorgenson and Griliches (1967). This captures substitutions among outputs of investment and consumption goods, as well inputs of capital and labour. We identify *information technology* (IT) with investments in computers, software, and communications equipment, as well as consumption of computer and software as outputs. The service flows from these assets are also inputs. The aggregate production function employed by Solow (1957, 1960) and, more recently by Greenwood, Hercowitz, and Krusell (1997), is an alternative to our model. In this approach, a single output is expressed as a function of capital and labour inputs. This implicitly assumes, however, that investments in information technology are perfect substitutes for other outputs, so that relative prices do not change.

Our methodology is essential in order to capture two important facts about which there is general agreement. The first is that the prices of computers have declined drastically relative to the prices of other investment goods. The second is that this rate of decline has recently accelerated. In addition, estimates of investment in software, now available in the NIPA, are comparable to investment in hardware. The new data show that the price of software has fallen relative to the prices of other investment goods, but more slowly than the price of hardware. We examine the estimates of software investment in some detail in order to assess the role of software in recent economic growth. Finally, we consider investment in communications equipment, which shares many of the technological features of computer hardware.

2.2.1.a Production Possibility Frontier

Aggregate output Y_t consists of investment goods I_t and consumption goods C_t. These outputs are produced from aggregate input X_t, consisting of capital services K_t and labour services L_t. We represent productivity as a "Hicks-neutral" augmentation A_t of aggregate input:[9]

(1) $$Y(I_t, C_t) = A_t \cdot X(K_t, L_t) .$$

The outputs of investment and consumption goods and the inputs of capital and labour services are themselves aggregates, each with many subcomponents.

Under the assumptions of competitive product and factor markets, and constant returns to scale, growth accounting gives the share-weighted growth of outputs as the sum of the share-weighted growth of inputs and growth in *total factor productivity* (TFP):

$$(2) \qquad \overline{w}_{I,t}\Delta \ln I_t + \overline{w}_{C,t}\Delta \ln C_t = \overline{v}_{K,t}\Delta \ln K_t + \overline{v}_{L,t}\Delta \ln L_t + \Delta \ln A_t \,,$$

where $\overline{w}_{I,t}$ is investment's average share of nominal output, $\overline{w}_{C,t}$ is consumption's average share of nominal output, $\overline{v}_{K,t}$ is capital's average share of nominal income, $\overline{v}_{L,t}$ is labour's average share of nominal income, $\overline{w}_{I,t} + \overline{w}_{C,t} = \overline{v}_{K,t} + \overline{v}_{L,t} = 1$, and Δ refers to a first difference. Note that we reserve the term *total factor productivity* for the augmentation factor in Equation (1).

Equation (2) enables us to identify the contributions of outputs and inputs to economic growth. For example, we can quantify the contributions of different investments, such as computers, software, and communications equipment, to the growth of output by decomposing the growth of investment among its components. Similarly, we can quantify the contributions of different types of consumption, such as services from computers and software, by decomposing the growth of consumption. As shown in Jorgenson and Stiroh (1999), both computer investment and consumption of IT have made important contributions to U.S. economic growth in the 1990s. We also consider the contributions to output of software and communications equipment as distinct high-tech assets. Similarly, we decompose the contribution of capital input to isolate the impact of computers, software, and communications equipment on input growth.

Rearranging Equation (2) enables us to present results in terms of growth in *average labour productivity* (ALP), defined as $y_t=Y_t/H_t$, where Y_t is output, defined as an aggregate of consumption and investment goods; $k_t=K_t/H_t$ is the ratio of capital services to hours worked H_t:

$$(3) \qquad \Delta \ln y_t = \overline{v}_{K,t}\Delta \ln k_t + \overline{v}_{L,t}\left(\Delta \ln L_t - \Delta \ln H_t\right) + \Delta \ln A_t \,.$$

This gives the familiar allocation of ALP growth among three factors. The first is *capital deepening*, the growth in capital services per hour. Capital deepening makes workers more productive by providing more capital for each hour of work and raises the growth of ALP in proportion to the share of capital. The second term is the improvement in *labour quality*, defined as the difference between growth rates of labour input and hours worked. Reflecting the rising proportion of hours supplied by workers with higher marginal products, labour quality improvement raises ALP growth in proportion to labour's share. The third factor is *total factor productivity* (TFP) growth, which increases ALP growth on a point-for-point basis.

2.2.1.b Computers, software, and communications equipment

We now consider the impact of investment in computers, software, and communications equipment on economic growth. For this purpose, we must carefully distinguish the *use* of information technology and the *production* of information technology.[10] For example, computers themselves are the output of one industry (the computer-producing industry, as part of Commercial and Industrial Machinery), and computing services are inputs into other industries (computer-using industries, like Trade, FIRE, and Services).

Massive increases in computing power, like those experienced by the U.S. economy, therefore reflect two effects on growth. First, as the production of computers improves and becomes more efficient, more computing power is being produced from the same inputs. This raises overall productivity in the computer-producing industry and contributes to TFP growth in the economy as a whole. Labour productivity also grows at both the industry and aggregate levels.[11]

Second, the rapid accumulation of computers leads to input growth of computing power in computer-using industries. Since labour is working with more and better computer equipment, this investment increases labour productivity. If the contributions to output are captured by the effect of capital deepening, aggregate TFP growth is unaffected. As Baily and Gordon (1988) remark, "there is no shift in the user firm's production function (p.378)," and thus no gain in TFP. Increasing deployment of computers increases TFP only if there are spillovers from the production of computers to production in the computer-using industries, or if there are measurement problems associated with the new inputs.

We conclude that rapid growth in computing power affects aggregate output through both TFP growth and capital deepening. Progress in the technology of computer production contributes to growth in TFP and ALP at the aggregate level. The accumulation of computing power in computer-using industries reflects the substitution of computers for other inputs and leads to growth in ALP. In the absence of spillovers, this growth does not contribute to TFP growth.

The remainder of this section provides empirical estimates of the variables in Equations (1) through (3). We then employ Equations (2) and (3) to quantify the sources of growth of output and ALP over 1959-1998 and various sub-periods.

2.2.2 Output

Our output data are based on the most recent benchmark revision of the NIPA.[12] Real output, Y_t, is measured in chained 1996 dollars, and $P_{Y,t}$ is the corresponding implicit deflator. Our output concept is similar, but not identical, to one used in the Bureau of Labor Statistics (BLS) productivity program. Like the BLS, we exclude the government sector, but unlike the BLS we include imputations for the flow of services from consumers' durables (CD) and owner-occupied housing. These imputations are necessary to preserve comparability between durables and housing; they also enable us to capture the important impact of information technology on households.

Our estimate of current dollar private output in 1998 is $8,013B, including imputations of $740B that primarily reflect the services of consumers' durables.[13] Real output growth was 3.63 percent for the whole period, compared to 3.36 percent for the official GDP series. The difference reflects both our imputations and our exclusion of the government sector in the NIPA data. Table A.1 in Appendix A shows the current dollar value and corresponding price index for total output and IT assets — investment in computers, I_c, investment in software, I_s, investment in communications equipment, I_m, consumption of computers and software, C_c, and the imputed service flow from consumers' computers and software, D_c.

The most striking feature of these data is the enormous price decline of computer investment — 18 percent per year from 1960 to 1995 (Figure 2.1). Since 1995 this decline has accelerated to 27.6 percent per year. By contrast, the relative price of software has been flat for much of the period and only began to fall in the late 1980s. The price of communications equipment behaves similarly to the price of software, while consumption of computers and software shows a decline similar to that of computer investment. The top panel of Table 2.1 summarizes the growth rates of prices and quantities of major output categories for 1990-95 and for 1995-98.

In terms of current dollar output, investment in software is the largest IT asset, followed by investment in computers and communications equipment (Figure 2.2). While business investments in computers, software, and communications equipment are by far the largest categories, households have spent more than $20B per year on computers and software since 1995, generating a service flow of comparable magnitude.

2.2.3 Capital Stock and Capital Services

This section describes our capital estimates for the U.S. economy from 1959 to 1998.[14] We begin with investment data from the Bureau of Economic Analysis, estimate capital stocks using the perpetual inventory method, and aggregate capital stocks using rental prices as weights. This approach, originated by Jorgenson and Griliches (1967), is based on the identification of rental prices with marginal products of different types of capital. Our estimates of these prices incorporate differences in asset prices, service lives and depreciation rates, and the tax treatment of capital income.[15]

We refer to the difference between growth in capital services and capital stock as the growth in *capital quality*, $q_{K,t}$; this represents a substitution towards assets with higher marginal products.[16] For example, the shift toward IT increases the quality of capital, since computers, software, and communications equipment are assets with relatively high marginal products. Capital stock estimates, like those originally employed by Solow (1957), fail to account for this increase in quality.

We employ a broad definition of capital, including tangible assets such as equipment and structures, as well as consumers' durables, land, and inventories. We estimate a service flow from the installed stock of consumers' durables, which enters our measures of both output and input. It is essential to include this service flow, since a steadily rising proportion is associated with investments in IT by the household sector. In order to capture the impact of information technology on U.S. economic growth, investments by the business and household sectors as well as the services of the resulting capital stocks must be included.

Table 2.1

Average Growth Rates of Selected Outputs and Inputs

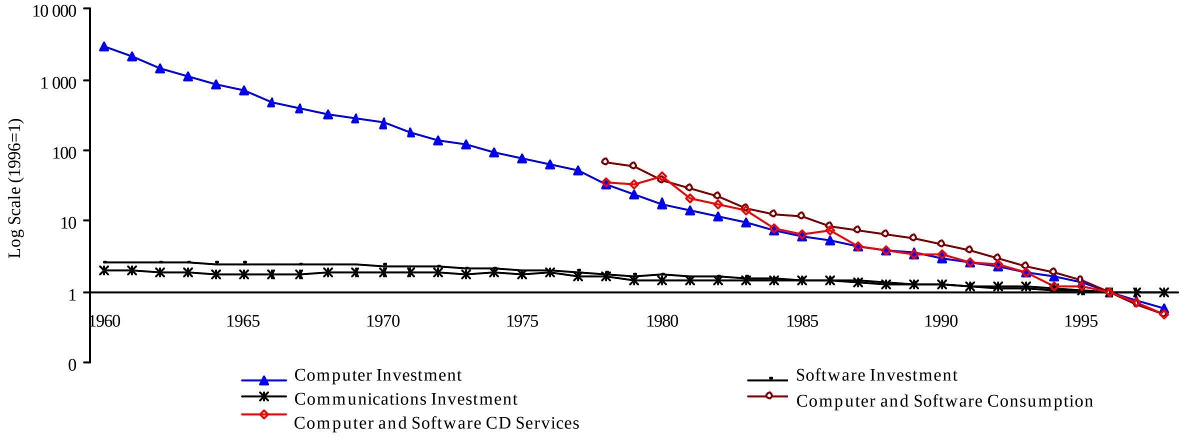
	1990-95		1995-98	
	Prices	Quantities	Prices	Quantities
	Outputs			
Private Domestic Output (Y)	1.70	2.74	1.37	4.73
Other (Y_n)	2.01	2.25	2.02	3.82
Computer and Software Consumption (C_c)	-21.50	38.67	-36.93	49.26
Computer Investment (I_c)	-14.59	24.89	-27.58	38.08
Software Investment (I_s)	-1.41	11.59	-2.16	15.18
Communications Investment (I_m)	-1.50	6.17	-1.73	12.79
Computer and Software CD Services (D_c)	-19.34	34.79	-28.62	44.57
	Inputs			
Total Capital Services (K)	0.60	2.83	2.54	4.80
Other (K_n)	1.00	1.78	4.20	2.91
Computer Capital (K_c)	-10.59	18.16	-20.09	34.10
Software Capital (K_s)	-2.07	13.22	-0.87	13.00
Communications Capital (K_m)	3.10	4.31	-7.09	7.80
Total Consumption Services (D)	1.98	2.91	-0.67	5.39
Non-Computer and Software (D_n)	2.55	2.07	0.54	3.73
Computer and Software CD Services (D_c)	-19.34	34.79	-28.62	44.57
Labour (L)	2.92	2.01	2.80	2.81

Note: CD refers to consumers' durable assets. All values are percentages.

Our estimate of capital stock is $26T in 1997, substantially larger than the $17.3T in fixed private capital estimated by the BEA (1998b). This difference reflects our inclusion of consumers’ durables, inventories, and land. Our estimates of capital stock for comparable categories of assets are quite similar to those of the BEA. Our estimate of fixed private capital in 1997, for example, is $16.8T, almost the same as that of the BEA. Similarly, our estimate of the stock of consumers' durables is $2.9T, while the BEA's estimate is $2.5T. The remaining discrepancies reflect our inclusion of land and inventories. Table B.1 in Appendix B lists the component assets and 1998 investment and stock values; Table B.2 presents the value of the capital stock from 1959 to 1998, as well as asset price indices for total capital and IT assets.

Figure 2.1

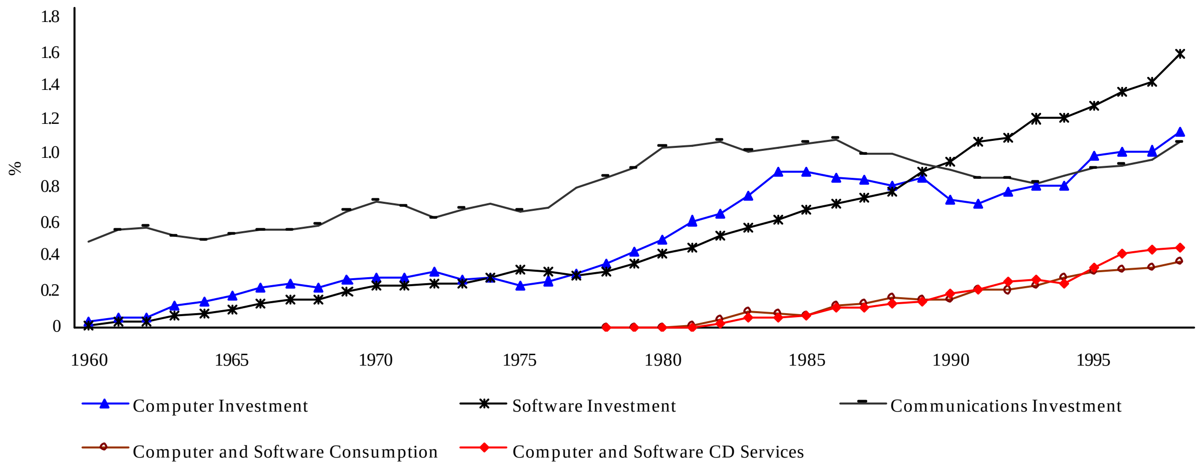
Relative Prices of Information Technology Outputs, 1960-98



Note: All price indices are relative to the output price index.

Figure 2.2

Output Shares of Information Technology, 1960-98



Note: Share of current dollar output.

The stocks of IT business assets (computers, software, and communications equipment), as well as consumers' purchases of computers and software, have grown dramatically in recent years, but remain relatively small. In 1998, combined IT assets accounted for only 3.4 percent of tangible capital, and 4.6 percent of reproducible, private assets.

We now move to estimates of capital service flows, where capital stocks of individual assets are aggregated using rental prices as weights. Table B.3 in Appendix B presents the current dollar service flows and corresponding price indices for 1959-98, and the second panel of Table 2.1 summarizes the growth rates of prices and quantities of inputs for 1990-95 and 1995-98.

There is a clear acceleration of growth of aggregate capital services from 2.8 percent per year for 1990-95 to 4.8 percent for 1995-98. It is largely due to a rapid growth in services from IT equipment and software, and reverses the trend toward slower capital growth through 1995. While information technology assets account for only 11.2 percent of the total, the service shares of these assets are much greater than the corresponding asset shares. In 1998, capital services were only 12.4 percent of capital stocks for tangible assets as a whole, but services were 40.0 percent of information technology stocks. This reflects the rapid price declines and high depreciation rates that enter into the rental prices of information technology.

Figure 2.3 highlights the rapid increase in the importance of IT assets, reflecting the accelerating pace of relative price declines. In the 1990s, the service price for computer hardware fell 14.2 percent per year, compared to an increase of 2.2 percent for non-information technology capital. As a direct consequence of this relative price change, computer services grew 24.1 percent, compared to only 3.6 percent for the services of non-IT capital during the 1990s. The current dollar share of services from computer hardware increased steadily and reached nearly 3.5 percent of all capital services in 1998 (Figure 2.3).[17]

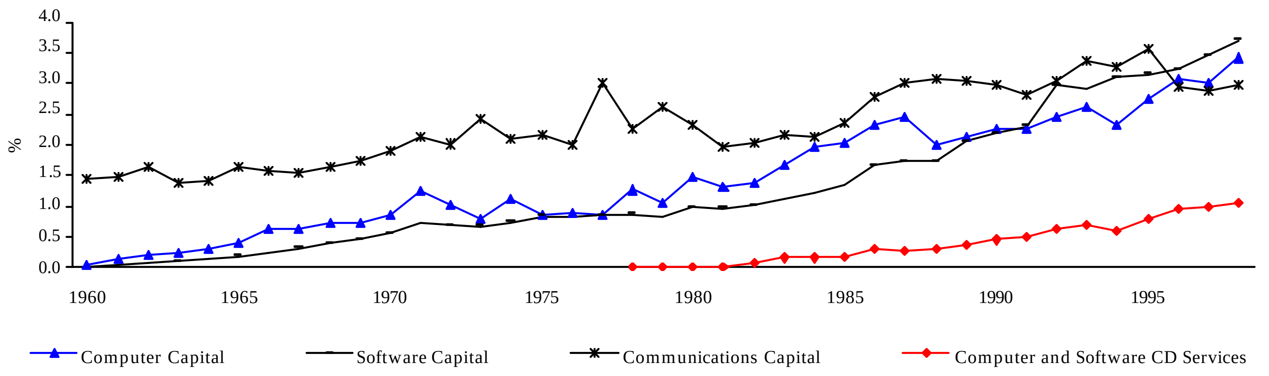
The rapid accumulation of software, however, appears to have different origins. The price of software investment has declined much more slowly (-1.7 percent per year for software versus -19.5 percent for computer hardware) from 1990 to 1998. These differences in investment prices lead to a much slower decline in service prices for software and computers, -1.6 percent versus -14.2 percent. Nonetheless, firms have been accumulating software quite rapidly, with real capital services growing 13.3 percent per year during the 1990s. While lower than the 24.1 percent growth recorded for computers, software growth is much more rapid than the growth of other forms of tangible capital. Complementarity between software and computers is one possible explanation. Firms respond to the decline in relative computer prices by accumulating computers and investing in complementary inputs like software to put the computers into operation.[18]

A competing explanation is that the official price indices used to deflate software investment omit a large part of true quality improvements. This would lead to a substantial overstatement of price inflation and a corresponding understatement of real investment, capital services, and economic growth. According to Moulton, Parker, and Seskin (1999), and Parker and Grimm (2000), only prices of pre-packaged software are calculated from constant-quality price deflators based on hedonic methods. Prices of business own-account software are based on input-cost indices, which implicitly assume no change in the productivity of computer programmers. Custom software prices are a weighted average of pre-packaged software and own-account software, with an arbitrary 75 percent weight given to business own-account software prices. Thus, the price deflators for nearly two-thirds of recent software investment are estimated under the maintained assumption of no gain in productivity.[19] If the quality of own-account and custom software is improving at a pace even remotely close to packaged software, this implies a large understatement of investment in software.

Although the price decline for communications equipment during the 1990s is comparable to that of software, as officially measured in the NIPA, investment has grown at a rate that is more in line with prices. However, there are also possible measurement biases in the pricing of communications equipment. 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 the BEA. Conventional price deflators are employed for transmission gear, such as fibre-optic cables, which also appear to be declining rapidly in price. This could lead to an underestimate of the rate of growth in communications equipment investment, capital stock, and capital services, as well as an overestimate of the rate of inflation.[20] We return to this issue at the end of Section 2.2.

Figure 2.3

Input Shares of Information Technology, 1960-98



Note: Share of current dollar capital and consumers' durable services.

2.2.4 Measuring Labour Services

This section describes our estimates of labour input for the U.S. economy from 1959 to 1998. We begin with individual data from the Census of Population for 1970, 1980, and 1990, as well as the annual Current Population Surveys. We estimate constant quality indices for labour input and its price to account for heterogeneity of the workforce across sexes, employment classes, age groups, and education levels. This follows the approach of Jorgenson, Gollop and Fraumeni (1987), whose estimates have been revised and updated by Ho and Jorgenson (1999).[21]

The distinction between labour input and labour hours is analogous to the distinction between capital services and capital stock. Growth in labour input reflects the increase in labour hours, as well as changes in the composition of hours worked as firms substitute among heterogeneous types of labour. We define the growth in labour quality as the difference between the growth in labour input and hours worked. Labour quality reflects the substitution of workers with high marginal products for those with low marginal products, while the growth in hours employed by Solow (1957) and others does not capture this substitution. Table C.1 in Appendix C presents our estimates of labour input, hours worked, and labour quality.

Our estimates show a value for labour expenditures of $4,546B in 1998, roughly 57 percent of the value of output. This share accurately includes private output and our imputations for capital services. If we exclude these imputations, labour's share rises to 62 percent, in line with conventional estimates. As shown in Table 2.1, the growth of the index of labour input, L_t, appropriate for our model of production in Equation (1) accelerated to 2.8 percent for 1995-98, from 2.0 percent for 1990-95. This is primarily due to the growth in the number of hours worked, which rose from 1.4 percent during 1990-95 to 2.4 percent during 1995-98, as the labour force participation increased and unemployment rates plummeted.[22]

The growth in labour quality decelerated in the late 1990s, from 0.65 percent during 1990-95 to 0.43 percent during 1995-98. This slowdown captures well-known underlying demographic trends in the composition of the workforce, as well as the exhaustion of the pool of available workers as unemployment rates steadily declined. Projections of future economic growth that omit labour quality, like those of the CBO discussed in Section 3, implicitly incorporate changes in labour quality into measured TFP growth. This reduces the reliability of projections of future economic growth. Fortunately, this is easily remedied by extrapolating demographic changes in the workforce in order to reflect foreseeable changes in the composition of workers by characteristics such as age, sex, and educational attainment.

2.2.5 Quantifying the Sources of Growth

Table 2.2 presents results of our growth accounting decomposition based on an extension of Equation (2) for the period 1959 to 1998 and various sub-periods, as well as preliminary estimates through 1999. As in Jorgenson and Stiroh (1999), we decompose economic growth by both output and input categories in order to quantify the contribution of information technology (IT) to investment and consumption outputs, as well as capital and consumers' durable inputs. We extend our previous treatment of the outputs and inputs of computers by identifying software and communications equipment as distinct IT assets.

To quantify the sources of IT-related growth more explicitly, we employ an extended production possibility frontier:

(4) $Y(Y_n,C_c,I_c,I_s,I_m,D_c) = A \cdot X\ (K_n, K_c, K_s, K_m,D_n,D_c,L)$

where outputs include computer and software consumption, C_c, computer investment, I_c, software investment, I_s, telecommunications investment, I_m, the services of consumers' computers and software, D_c, and other outputs, Y_n. Inputs include the capital services of computers, K_c, software, K_s, telecommunications equipment, K_m, other capital assets, K_n, services of consumers' computers and software, D_c, other durables, D_n, and labour input, L.[23] As in Equation (1), total factor productivity is denoted by A and represents the ability to produce more output from the same inputs. Time subscripts have been dropped for convenience.

The corresponding extended growth accounting equation is:

(5) $$\bar{w}_{Yn}\Delta\ln Y_n + \bar{w}_{Cc}\Delta\ln C_c + \bar{w}_{Ic}\Delta\ln I_c + \bar{w}_{Is}\Delta\ln I_s + \bar{w}_{Im}\Delta\ln I_m + \bar{w}_{Dc}\Delta\ln D_c = \bar{v}_{Kn}\Delta\ln K_n + \bar{v}_{Kc}\Delta\ln K_c + \bar{v}_{Ks}\Delta\ln K_s + \bar{v}_{Km}\Delta\ln K_m + \bar{v}_{Dn}\Delta\ln D_n + \bar{v}_{Dc}\Delta\ln D_c + \bar{v}_{L}\Delta\ln L + \Delta\ln A$$

where $\overline{w}$ and $\overline{v}$ denote the average shares of nominal income for the subscripted variable $\overline{w}_{Yn}+\overline{w}_{Cc}+\overline{w}_{Ic}+\overline{w}_{Is}+\overline{w}_{\mathrm{Im}}+\overline{w}_{Dc}=\overline{v}_{Kn}+\overline{v}_{Kc}+\overline{v}_{Ks}+\overline{v}_{Km}+\overline{v}_{Dn}+\overline{v}_{Dc}+\overline{v}_{L}=1$; we refer to a share-weighted growth rate as the *contribution* of an input or output.

2.2.5.a Output Growth

We first consider the sources of output growth for the entire period 1959 to 1998. Broadly defined capital services make the largest contribution to growth with 1.8 percentage points (1.3 percentage points from business capital and 0.5 from consumers' durable assets), labour services contribute 1.2 percentage points, and TFP growth is responsible for only 0.6 percentage points. Input growth is the source of nearly 80 percent of U.S. economic growth over the past 40 years, while TFP has accounted for approximately one-fifth. Figure 2.4 highlights this result by showing the relatively small contribution to growth of the TFP residual in each sub-period.

More than three-quarters of the contribution of broadly defined capital reflects the accumulation of capital stock, while increased labour hours account for slightly less than three-quarters of labour's contribution. The quality of both capital and labour have made important contributions, with 0.45 and 0.32 percentage points per year, respectively. Accounting for substitution among heterogeneous capital and labour inputs is therefore an important part of quantifying the sources of economic growth.

A look at the U.S. economy before and after 1973 reveals some familiar features of the historical record. After strong output and TFP growth in the 1960s and early 1970s, the U.S. economy slowed markedly through 1990, with annual output growth falling from 4.3 percent to 3.1 percent and annual TFP growth falling almost two-thirds of a percentage point from 1.0 percent to 0.3 percent. Growth in capital inputs also slowed, falling from 5.0 percent during 1959-73 to 3.8 percent during 1973-90, which contributed to a sluggish ALP growth of 2.9 percent during 1959-73 to 1.4 percent during 1973-90.

We now focus on the 1990s and highlight recent changes.[24] Relative to the early 1990s, output growth has increased by nearly 2.0 percentage points during 1995-98. The contribution of capital jumped by 1.0 percentage point, the contribution of labour rose by 0.4 percentage points, and TFP growth accelerated by 0.6 percentage points. ALP growth rose 1.0 percentage point. The rising contributions of capital and labour encompass several well-known trends in the late 1990s. Growth in hours worked accelerated as labour markets tightened, unemployment fell to a 30-year low, and labour force participation rates increased.[25] The contribution of capital reflects the investment boom of the late 1990s as businesses poured resources into plant and equipment, especially computers, software, and communications equipment.

The acceleration of TFP growth is perhaps the most remarkable feature of the data. After averaging only 0.34 percent per year from 1973 to 1995, the acceleration of TFP to 0.99 percent suggests massive improvements in technology and increases in the efficiency of production. While the resurgence of TFP growth in the 1990s has yet to surpass that recorded in the 1960s and early 1970s, more rapid TFP growth is critical for sustained higher rates of growth.

Figures 2.5 and 2.6 highlight the rising contributions of information technology (IT) outputs to U.S. economic growth. Figure 2.5 shows the breakdown between IT and non-IT outputs for the sub-periods from 1959 to 1998, while Figure 2.6 decomposes the contribution of IT outputs into the five components identified above. Although the role of IT has steadily increased, Figure 2.5 shows that the recent surge in investment and consumption nearly doubled the contribution to output of IT during 1995-98 relative to 1990-95. Figure 2.6 shows that computer investment is the largest single IT contributor in the late 1990s, and that consumption of computers and software is becoming increasingly important as a source of output growth.

Figures 2.7 and 2.8 present a similar decomposition of the role of IT as a production input, where the contribution is rising even more dramatically. Figure 2.7 shows that the capital and consumers' durable contribution from IT increased rapidly in the late 1990s, and now accounts for more than two-fifths of the total contribution to growth from broadly defined capital. Figure 2.8 shows that computer hardware is also the single largest IT contributor on the input side, which reflects the growing share and rapid growth rates of the late 1990s.

Table 2.2

Growth in U.S. Private Domestic Output and the Sources of Growth, 1959-99

						Preliminary*
	1959-98	**1959-73**	**1973-90**	**1990-95**	**1995-98**	**1995-99**
Growth in Private Domestic Output (Y)	3.630	4.325	3.126	2.740	4.729	4.763
Contribution of Selected Output Components						
Other (Y_n)	3.275	4.184	2.782	2.178	3.659	3.657
Computer and Software Consumption (C_c)	0.035	0.000	0.023	0.092	0.167	0.175
Computer Investment (I_c)	0.150	0.067	0.162	0.200	0.385	0.388
Software Investment (I_s)	0.074	0.025	0.075	0.128	0.208	0.212
Communications Investment (I_m)	0.060	0.048	0.061	0.053	0.122	0.128
Computer and Software CD Services (D_c)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Capital Services (K)	1.260	1.436	1.157	0.908	1.611	1.727
Other (K_n)	0.936	1.261	0.807	0.509	0.857	0.923
Computers (K_c)	0.177	0.086	0.199	0.187	0.458	0.490
Software (K_s)	0.075	0.026	0.071	0.154	0.193	0.205
Communications (K_m)	0.073	0.062	0.080	0.058	0.104	0.109
Contribution of CD Services (D)	0.510	0.632	0.465	0.292	0.558	0.608
Other (D_n)	0.474	0.632	0.442	0.202	0.370	0.403
Computers and Software (D_c)	0.036	0.000	0.023	0.089	0.187	0.204
Contribution of Labour (L)	1.233	1.249	1.174	1.182	1.572	1.438
Aggregate Total Factor Productivity (TFP)	0.628	1.009	0.330	0.358	0.987	0.991
Growth of Capital and CD Services	4.212	4.985	3.847	2.851	4.935	5.286
Growth of Labour Input	2.130	2.141	2.035	2.014	2.810	2.575

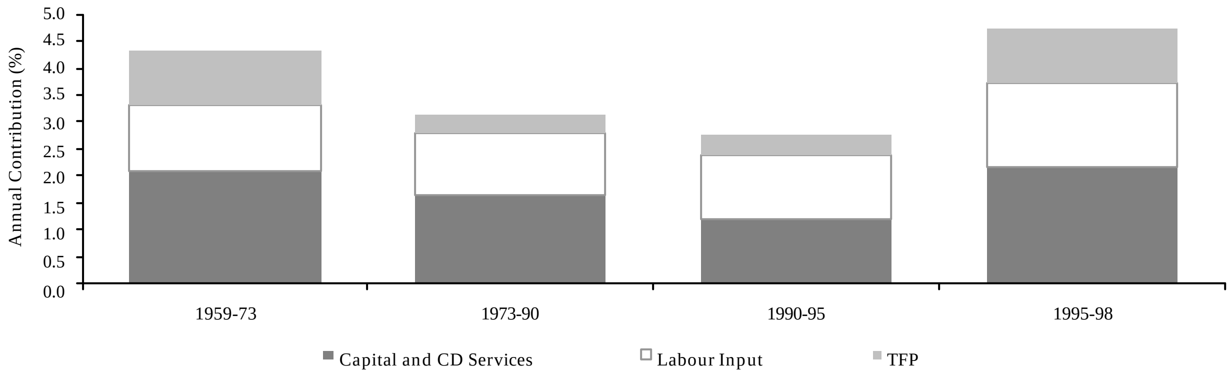
Table 2.2 (cont'd)

					Preliminary*
	1959-98	**1959-73**	**1973-90**	**1990-95**	**1995-98**	**1995-99**
Contribution of Capital and CD Quality	0.449	0.402	0.405	0.434	0.945	1.041
Contribution of Capital and CD Stock	1.320	1.664	1.217	0.765	1.225	1.293
Contribution of Labour Quality	0.315	0.447	0.200	0.370	0.253	0.248
Contribution of Labour Hours	0.918	0.802	0.974	0.812	1.319	1.190
Average Labour Productivity (*ALP*)	2.042	2.948	1.437	1.366	2.371	2.580

Note: The contribution of an output or an input is defined as the share-weighted, real growth rate. CD refers to consumers' durable assets. All values are percentages. 1995-99 results include preliminary estimates for 1999; see the Annex to this chapter for details on estimation and data sources.

Figure 2.4

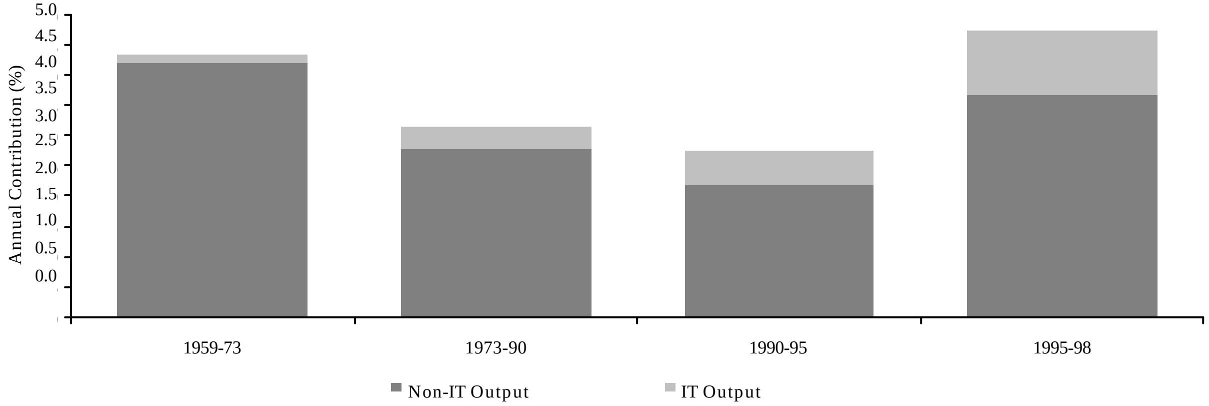
Sources of U.S. Economic Growth, 1959-98



Note: An inp ut's contribution is its average share-weighted, annual growth rate. TFP defined in Equation (2) in the text.

Figure 2.5

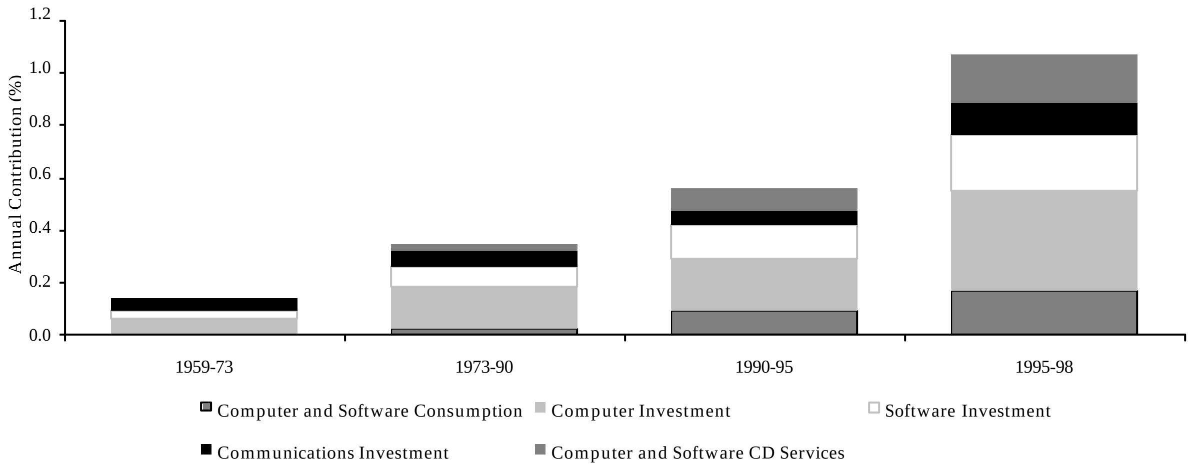
Contribution to Output of Information Technology, 1959-98



Note: The contribution of an output is its average share-weighted, annual growth rate.

Figure 2.6

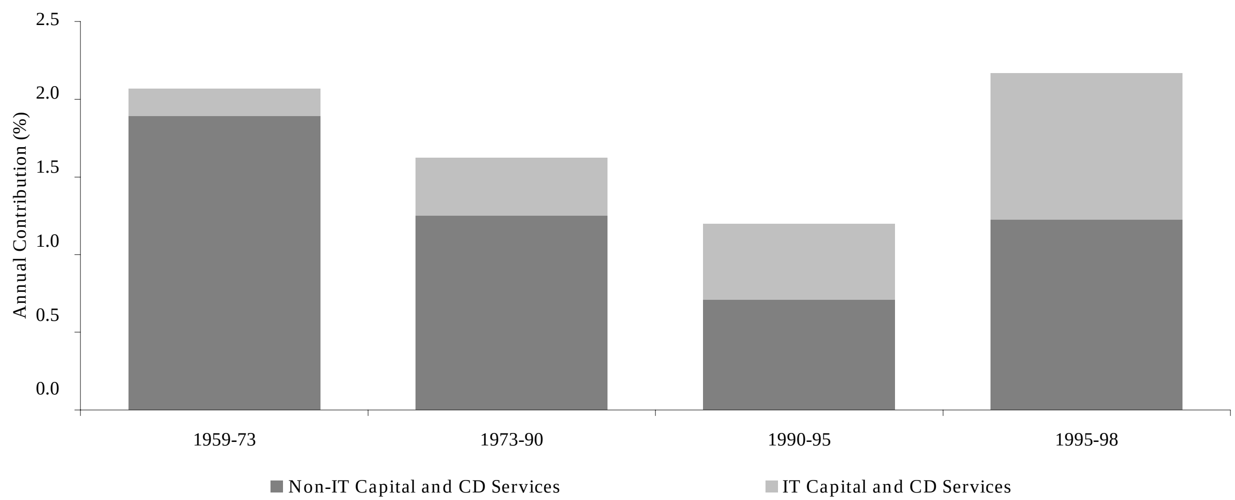
Contribution to Output of Information Technology Assets, 1959-98



Note: The contribution of an output is its average share-weighted, annual growth rate.

Figure 2.7

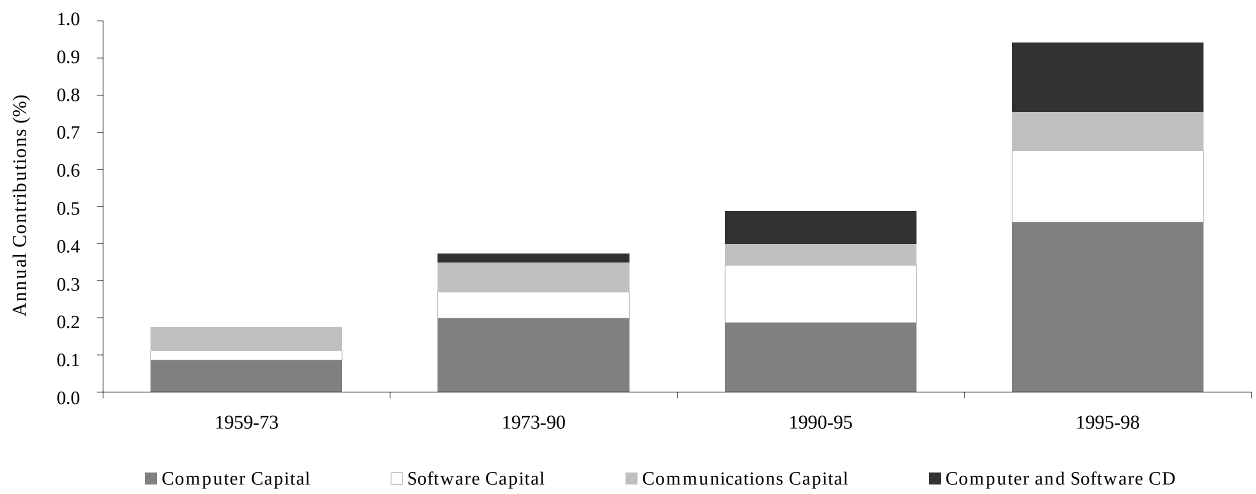
Input Contribution of Information Technology, 1959-98



Note: The contribution of an output is its average share-weighted, annual growth rate.

Figure 2.8

Input Contribution of Information Technology Assets, 1959-98



Note: The contribution of an output is its average share-weighted, annual growth rate.

The contribution of computers, software, and communications equipment offers a different picture from that presented by Jorgenson and Stiroh (1999) for both data and methodological reasons. First, the BEA benchmark revision has classified software as an investment good. While software is growing more slowly than computers, the substantial nominal share of software services has raised the contribution of information technology. Second, we have added communications equipment, also a slower growing component of capital services, with similar effects. Third, we now incorporate asset-specific revaluation terms in all rental price estimates. Since the acquisition prices of computers are steadily falling, asset-specific revaluation terms have raised the estimated service price and increased the share of computer services. Finally, we have modified our timing convention and now assume that capital services from individual assets are proportional to the average of the current and lagged stock. For assets with relatively short service lives like IT, this is a more reasonable assumption than in our earlier work, which assumed that it took a full year for new investment to become productive.[26]

This large increase in the contribution of computers and software to growth is consistent with recent estimates by Oliner and Sichel (2000), although their estimate of such contribution is somewhat larger. They report that computer hardware and software contributed 0.93 percentage points to growth during 1996-99, while communications contributed another 0.15. The discrepancy primarily reflects our broader output concept, which lowers the input share of these high-tech assets, and also minor differences in tax parameters and stock estimates. Whelan (1999) also reports a larger contribution to growth of 0.82 percentage points from computer hardware over 1996-98. The discrepancy also reflects our broader output concept. In addition, Whelan (1999) introduces a new methodology to account for retirement and support costs that generates a considerably larger capital stock and raises the input share and the contribution of computer capital to growth.

Despite differences in methodology and data sources among studies, a consensus is building that computers are having a substantial impact on economic growth.[27] What is driving the increase in the contributions of computers, software, and communications equipment? As we argued in Jorgenson and Stiroh (1999), price changes lead to substitution toward capital services with lower relative prices. Firms and consumers are responding to relative price changes.

Table 2.1 shows that the acquisition price of computer investment fell nearly 28 percent per year, the price of software fell 2.2 percent, and the price of communications equipment fell 1.7 percent during the period 1995-98, while other output prices rose 2.0 percent. In response to these price changes, firms accumulated computers, software, and communications equipment more rapidly than other forms of capital. Investment other than information technology actually declined as a proportion of the private domestic product. The story of household substitution toward computers and software is similar. These substitutions suggest that the gains from the computer revolution accrue to firms and households that are adept at restructuring activities to respond to these relative price changes.

2.2.5.b Average Labour Productivity Growth

To provide a different perspective on the sources of economic growth we can look at ALP growth. By simple arithmetic, output growth equals the sum of the growth in hours of work and the growth in labour productivity.[28] Table 2.3 shows the output breakdown between growth in hours worked and ALP for the same periods as in Table 2.2. For the entire period 1959-1998, ALP growth was the predominant determinant of output growth, increasing just over 2 percent per year over 1959-98, while the number of hours increased about 1.6 percent per year. We then examine the changing importance of the factors determining ALP growth. As shown in Equation (3), ALP growth depends on a capital deepening effect, a labour quality effect, and a TFP effect.

Table 2.3

The Sources of ALP Growth, 1959-98

Variable	1959-98	1959-73	1973-90	1990-95	1995-98
Growth of Private Domestic Output (*Y*)	3.630	4.325	3.126	2.740	4.729
Growth in Hours Worked (*H*)	1.588	1.377	1.689	1.374	2.358
Growth in ALP (*Y/H*)	2.042	2.948	1.437	1.366	2.371
Contribution of Capital Deepening to ALP	1.100	1.492	0.908	0.637	1.131
Contribution of Labour Quality to ALP	0.315	0.447	0.200	0.370	0.253
Contribution of TFP to ALP	0.628	1.009	0.330	0.358	0.987

Note: Contributions to ALP are defined in Equation (3). All values are percentages.

Figure 2.9 plots the importance of each factor, revealing the well-known productivity slowdown of the 1970s and 1980s, and highlighting the acceleration of labour productivity growth in the late 1990s. The slowdown through 1990 reflects a lesser capital deepening, declining labour quality growth, and decelerating growth in TFP. The growth of ALP slipped further during the early 1990s with the serious slump in capital deepening only partly offset by a revival in the growth of labour quality and an uptick in TFP growth. Slow growth in hours worked combined with a slow ALP growth during 1990-95 to produce a further slide in the growth of output. This stands out from previous cyclical recoveries during the post-war period, when output growth accelerated during the recovery, powered by a more rapid growth in hours worked and ALP.

For the most recent period of 1995-98, strong output growth reflects growth in labour hours and ALP almost equally. Comparing 1990-95 to 1995-98, output growth accelerated by nearly 2.0 percentage points due to a 1.0 percentage point increase in hours worked, and a 1.0 percentage point increase in ALP growth.[29] Figure 2.9 shows that the acceleration in ALP growth is due to rapid capital deepening from the investment boom, as well as faster TFP growth. Capital deepening contributed 0.49 percentage points to the acceleration in ALP growth, while acceleration in TFP growth added 0.63 percentage points. Growth in labour quality slowed somewhat as growth in hours worked accelerated. This reflects the falling unemployment rate and a tightening of labour markets as more workers with relatively low marginal products were drawn into the workforce. Oliner and Sichel (2000) also show a decline in the contribution of labour quality to growth in the late 1990s, from 0.44 during 1991-95 to 0.31 during 1996-99.

Our decomposition also sheds some light on the hypothesis advanced by Gordon (1999b), who argues that the vast majority of recent ALP gains are due to the production of IT, particularly computers, rather than to the use of IT. As we have already pointed out, more efficient IT production generates aggregate TFP growth as more computing power is produced from the same inputs, while IT use affects ALP growth via capital deepening. In recent years, the acceleration of TFP growth was a slightly more important factor in the acceleration of ALP growth than capital deepening. Efficiency gains in computer production are an important part of aggregate TFP growth, as Gordon's results on ALP suggest. We return to this issue in greater detail below.

Figure 2.9

Sources of U.S. Labour Productivity Growth, 1959-98

Note: Annual contributions are defined in Equation (3) in the text.

2.2.5.c Total Factor Productivity Growth

Finally, we consider the remarkable performance of U.S. TFP growth in recent years. After maintaining an average rate of 0.33 percent for the period 1973-90, TFP growth rose to 0.36 percent during 1990-95 and then vaulted to 0.99 percent per year during 1995-98. This jump is a major source of growth in output and ALP for the U.S. economy (Figures 2.4 and 2.9). While TFP growth in the 1990s has yet to attain the peaks recorded for some periods in the golden age of the 1960s and early 1970s, the recent acceleration suggests that the U.S. economy may be recovering from the anaemic productivity growth of the past two decades. Of course, caution is warranted until more historical experience is available.

As early as Domar (1961), economists have utilized a multi-industry model of the economy to trace aggregate productivity growth to its sources at the level of individual industries. Jorgenson, Gollop, and Fraumeni (1987), and Jorgenson (1990) have employed this model to identify industry-level sources of growth. More recently, Gullickson and Harper (1999), and Jorgenson and Stiroh (2000) have used the model for similar purposes. We postpone more detailed consideration of these sources of TFP growth until we have examined the impact of alternative price deflators on our decomposition of growth.

2.2.6 Alternative Growth Accounting Estimates

Tables 2.1 through 2.3 and Figures 2.1 through 2.9 report our primary results using the official data published in the NIPA. As we have already noted, however, there is reason to believe that the rates of inflation in official price indices for certain high-tech assets, notably software and telecommunications equipment, may be overstated. Moulton, Parker, and Seskin (1999), and Parker and Grimm (2000), for example, report that only the pre-packaged segment of software investment is deflated with a constant-quality deflator. Own-account software is deflated with an input cost index and custom software is deflated with a weighted average of the pre-packaged and own-account deflator. Similarly, BEA reports that in the communications equipment category, only telephone switching equipment is deflated with a constant-quality, hedonic price deflator.

This subsection incorporates alternative price series for software and communications equipment and examines the impact on the estimates of U.S. economic growth and its sources. Table 2.4 presents growth accounting results under three different scenarios. The Base case repeats the estimates from Table 2.2, which are based on official NIPA price data. Two additional cases, Moderate Price Decline and Rapid Price Decline, incorporate price series for software and communications equipment that show faster price declines and correspondingly more rapid real investment growth.[30]

The Moderate Price Decline case assumes that pre-packaged software prices are appropriate for all types of private software investment, including custom and business own-account software. Since the index for pre-packaged software is based on explicit quality adjustments, it falls much faster than the prices of custom and own-account software, -10.1 percent vs. 0.4 percent and 4.1 percent, respectively, for the full period 1959-98 according to Parker and Grimm (2000). For communications equipment, the data are more limited and we assume prices fell 10.7 percent per year throughout the entire period. This estimate is the average annual "smoothed" decline for digital switching equipment over 1985-96, as reported by Grimm (1997). While this series may not be appropriate for all types of communications equipment, it exploits the best available information.

The Rapid Price Decline case assumes that software prices fell 16 percent per year during 1959-98, the rate of quality-adjusted price decline reported by Brynjolfsson and Kemerer (1996) for microcomputer spreadsheets over 1987-92. This is a slightly faster rate of decline than the -15 percent estimated by Gandal (1994) for 1986-91, and considerably faster than the 3 percent annual decline for word processors, spreadsheets, and databases reported by Oliner and Sichel (1994) for 1987-93. For communications equipment, we used estimates from the most recent period from Grimm (1997), who reports a decline of 17.9 percent per year over 1992-96.

While this exercise necessarily involves some arbitrary choices, the estimates incorporate the limited data now available and provide a valuable perspective on the crucial importance of accounting for quality changes in the prices of investment goods. Comparisons among the three cases are also useful for suggesting the range of uncertainty currently confronting analysts of U.S. economic growth.

Before discussing the empirical results, it is worthwhile to emphasize that a more rapid price decline for information technology has two direct effects on the sources of growth, and one indirect effect. The alternative investment deflators raise real output growth by reallocating nominal growth away from prices towards quantities. This also increases the growth rate of capital stock, since there are larger investment quantities in each year. More rapid price declines also give greater weight to capital services from information technology.

The counter-balancing effects of increased output and increased input growth lead to an indirect effect on measured TFP growth. Depending on the relative shares of high-tech assets in investment and capital services, the TFP residual will either increase if the output effect dominates or decrease if the effect on capital services dominates.[31] Following Solow (1957, 1960), Greenwood, Hercowitz, and Krusell (1997) we omit the output effect and attribute the input effect to "investment-specific" (embodied) technical change. This must be carefully distinguished from the effects of industry-level productivity growth on TFP growth, discussed in Section 4.

Table 2.4 reports growth accounting results from these three scenarios: Base case, Moderate Price Decline, and Rapid Price Decline. The results are not surprising; the more rapid the price decline for software and communications equipment, the faster the rate of growth of output and capital services. Relative to the Base case, output growth increases by 0.16 percentage points per year over 1995-98 in the Moderate Price Decline case and by 0.34 percentage points in the Rapid Price Decline case. Capital input growth shows slightly larger increases across the three cases. Clearly, constant-quality price indices for information technology are essential to further progress in understanding the impact on growth of high-tech investment.

The acceleration of output and input growth reflects the increased contributions from IT, and determines the effect on the TFP residual. In particular, the contribution of software to output for 1995-98 increases from 0.21 percentage points in the Base case to 0.29 percentage points in the Moderate Price Decline case, and to 0.40 percentage points in the Rapid Price Decline case. Similarly, the capital services contribution for software increases from 0.19 to 0.29 and to 0.45 percentage points. The contribution of communications equipment shows similar changes. Residual TFP growth fell slightly during the 1990s, as the input effect outweighed the output effect, due to the large capital services shares of IT.

Table 2.4

Growth in U.S. Private Domestic Output and the Sources of Growth, 1959-99

	Base Case				Moderate Price Decline				Rapid Price Decline			
	1959-73	1973-90	1990-95	1995-98	1959-73	1973-90	1990-95	1995-98	1959-73	1973-90	1990-95	1995-98
Growth in Private Domestic Output (Y)	4.33	3.13	2.74	4.73	4.35	3.30	2.90	4.89	4.36	3.38	3.03	5.07
Contribution of Selected Output Components												
Other (Y_n)	4.18	2.78	2.18	3.66	4.12	2.76	2.17	3.66	4.08	2.75	2.16	3.66
Computer and Software Consumption (C_c)	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17	0.00	0.02	0.09	0.17
Computer Investment (I_c)	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39	0.07	0.16	0.20	0.39
Software Investment (I_s)	0.03	0.08	0.13	0.21	0.04	0.14	0.22	0.29	0.05	0.17	0.29	0.40
Communications Equipment Investment (I_m)	0.05	0.06	0.05	0.12	0.12	0.19	0.13	0.21	0.16	0.25	0.19	0.27
Computer and Software CD Services (D_c)	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
Contribution of Capital Services (K)	1.44	1.16	0.91	1.61	1.54	1.39	1.15	1.83	1.61	1.51	1.32	2.09
Other (K_n)	1.26	0.81	0.51	0.86	1.25	0.80	0.51	0.86	1.25	0.79	0.51	0.85
Computers (K_c)	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46	0.09	0.20	0.19	0.46
Software (K_s)	0.03	0.07	0.15	0.19	0.05	0.15	0.28	0.29	0.06	0.18	0.36	0.45
Communications Equipment (K_m)	0.06	0.08	0.06	0.10	0.16	0.25	0.18	0.23	0.22	0.34	0.27	0.33
Contribution of CD Services (D)	0.63	0.47	0.29	0.56	0.63	0.46	0.29	0.56	0.63	0.46	0.29	0.56
Non-Computers and Software (D_n)	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37	0.63	0.44	0.20	0.37
Computers and Software (D_c)	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19	0.00	0.02	0.09	0.19
Contribution of Labour (L)	1.25	1.17	1.18	1.57	1.25	1.17	1.18	1.57	1.25	1.18	1.18	1.57
Aggregate Total Factor Productivity (TFP)	1.01	0.33	0.36	0.99	0.94	0.27	0.27	0.93	0.88	0.22	0.23	0.85

Table 2.4 (cont'd)

	Base Case				Moderate Price Decline				Rapid Price Decline			
	1959 -73	**1973 -90**	**1990 -95**	**1995 -98**	**1959 -73**	**1973 -90**	**1990 -95**	**1995 -98**	**1959 -73**	**1973 -90**	**1990 -95**	**1995 -98**
Growth of Capital and CD Services	4.99	3.85	2.85	4.94	5.24	4.40	3.43	5.44	5.41	4.70	3.84	6.02
Growth of Labour Input	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81	2.14	2.04	2.01	2.81
Contribution of Capital and CD Quality	0.40	0.41	0.43	0.95	0.48	0.59	0.63	1.11	0.54	0.70	0.78	1.34
Contribution of Capital and CD Stock	1.66	1.22	0.77	1.23	1.68	1.26	0.82	1.28	1.69	1.27	0.84	1.31
Contribution of Labour Quality	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25	0.45	0.20	0.37	0.25
Contribution of Labour Hours	0.80	0.97	0.81	1.32	0.80	0.97	0.81	1.32	0.80	0.98	0.81	1.32
Average Labour Productivity (*ALP*)	2.95	1.44	1.37	2.37	2.98	1.61	1.52	2.53	2.99	1.69	1.65	2.72

Note: The Base case uses official NIPA price data. The Moderate Price Decline case uses the pre-packaged software deflator for all software and annual price changes of -10.7 percent for communications equipment. The Rapid Price Decline case uses annual price changes of -16 percent for software and -17.9 percent for communications equipment. See text for details and sources. A contribution is defined as the share-weighted, real growth rate. CD refers to consumers' durable assets. All values are percentages.

This exercise illustrates the sensitivity of the sources of growth to alternative information technology price indices. We do not propose to argue the two alternative cases are more nearly correct than the Base case with the official prices from NIPA. Given the paucity of quality-adjusted price data on high-tech equipment, we simply do not know. Rather, we have tried to highlight the importance of correctly measuring prices and quantities to understand the dynamic forces driving economic growth in the United States. As high-tech assets continue to proliferate through the economy and other investment goods become increasingly dependent on electronic components, these measurement issues will become increasingly important. While the task that lies ahead of us will be onerous, the creation of quality-adjusted price indices for all high-tech assets deserves top priority.

2.2.7 Decomposition of TFP Growth

We next consider the role of high-tech industries as a source of TFP growth. As discussed above, the production of high-tech investment goods has made an important contribution to aggregate growth. CEA (2000), for example, allocates 0.39 percentage points of aggregate TFP growth to computer production, while Oliner and Sichel (2000) allocate 0.47 percentage points to the production of computers and computer-related semi-conductors for the period 1995-99.[32]

We employ a methodology based on the price "dual" approach to measurement of productivity at the industry level. Anticipating our complete industry analysis presented in Section 4, below, it is worthwhile to spell out the decomposition of TFP growth by industry. Using the Domar approach to aggregation, industry-level productivity growth is weighted by the ratio of the gross output of each industry to aggregate value-added in order to estimate the industry contribution to aggregate TFP growth. In the dual approach, 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.

In the case of computer production, this expression is dominated by two terms; namely, the price of computers and the price of semi-conductors, a primary intermediate input to the computer-producing industry. If semi-conductor industry output is used only as an intermediate good to produce computers, then its contribution to the productivity growth of the computer industry, weighted by computer industry output, precisely cancels its independent contribution to aggregate TFP growth.[33] This independent contribution from the semi-conductor industry, based on the complete Domar weighting scheme, is the value of semi-conductor output divided by aggregate value added, multiplied by the rate of price decline in semi-conductors.

In Table 2.5, we report details of our TFP decomposition for the three alternative cases described above for 1990-95 and 1995-98 and summarize the IT vs. non-IT comparison in Figure 2.10. In our Base case, using official NIPA data, we estimate that the production of information technology accounts for 0.44 percentage points in 1995-98, compared to 0.25 percentage points in 1990-95. This reflects the accelerating relative price changes due to a radical shortening of the product cycle of semi-conductors.[34]

As we have already noted, the estimates of price declines for high-tech investments in our Base case calculations may be conservative; in fact, these estimates may be *very* conservative. Consider the Moderate Price Decline case, which reflects only part of the data we would require for constant-quality estimates of the information technology price declines. This boosts the contribution of information technology to TFP growth to 0.64 percentage points, an increase of 0.20 percentage points for 1995-98. Proceeding to what may appear to be the outer limit of plausibility, but still consistent with the available evidence, we can consider the Rapid Price Decline case. The contribution of information technology to TFP growth is now a robust 0.86 percentage points, accounting for all of TFP growth during 1995-98.

As a final observation from the TFP decomposition, we note that the acceleration of TFP in the late 1990s does not appear to be entirely located within IT-producing industries. While the actual growth rates vary considerably across our three alternative cases, non-IT TFP growth increased markedly in each case when the early 1990s are compared to the late 1990s. This runs counter to the conclusion of Gordon (1999b), who reports that the entire acceleration of labour productivity growth in the late 1990s reflects gains in IT-production. This divergence likely reflects Gordon's detrending procedure, which attributes a sizeable portion of the recent productivity growth to cyclical factors, as well as his focus on labour productivity and our focus on TFP growth.

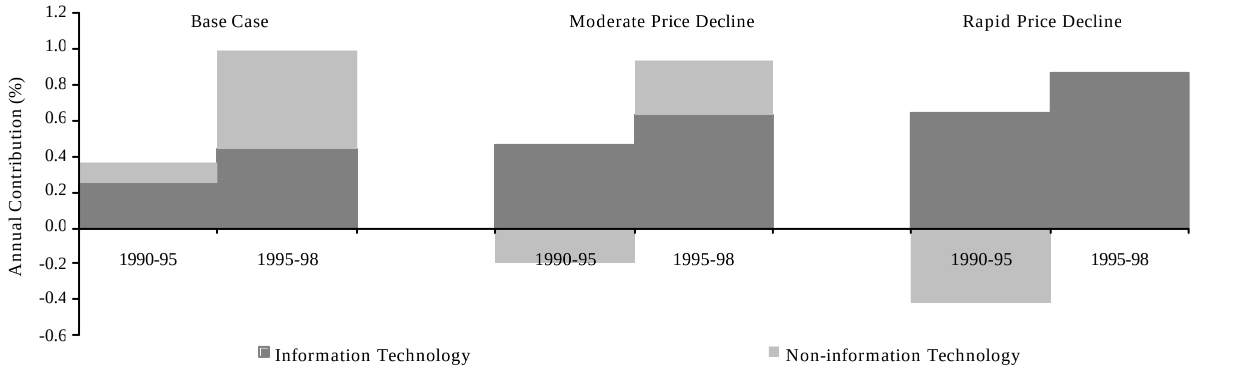
Table 2.5
Information Technology Decomposition of TFP Growth for Alternative Deflation Cases, 1990-98

	Base Case		Moderate Price Decline		Rapid Price Decline	
	1990-95	1995-98	1990-95	1995-98	1990-95	1995-98
Aggregate TFP Growth	0.36	0.99	0.27	0.93	0.23	0.85
	TFP Contribution					
Information Technology	0.25	0.44	0.46	0.64	0.64	0.86
Computers	0.16	0.32	0.16	0.32	0.16	0.32
Software	0.05	0.08	0.17	0.18	0.28	0.34
Communications Equipment	0.04	0.04	0.13	0.13	0.21	0.20
Non-information Technology	0.11	0.55	-0.19	0.29	-0.41	-0.01
	Relative Price Change					
Computers	-16.6	-29.6	-16.6	-29.6	-16.6	-29.6
Software	-3.4	-4.2	-11.3	-9.7	-18.0	-18.0
Communications Equipment	-3.5	-3.8	-12.7	-12.7	-19.9	-19.9
	Average Nominal Share					
Computers	0.96	1.09	0.96	1.09	0.96	1.09
Software	1.54	1.88	1.54	1.88	1.54	1.88
Communications Equipment	1.05	1.02	1.05	1.02	1.05	1.02

Note: The Base case uses official NIPA price data. The Moderate Price Decline case uses the pre-packaged software deflator for all software and -10.7 percent for communications equipment. The Rapid Price Decline case uses -16 percent for software and -17.9 percent for communications equipment. See the text for details and sources. A TFP contribution is defined as the share-weighted growth rate of relative prices.

Figure 2.10

TFP Decomposition for Alternative Deflation Cases



Note: The annual contribution of information technology is the share-weighted decline in relative prices.

This acceleration of non-IT TFP growth could also be interpreted as evidence of a "new economy." If these productivity gains do indeed reflect spillovers from IT into non-IT industries, this would provide some missing evidence for the new economy side. Alternatively, this could reflect technological progress in non-IT industries that is entirely independent of the IT revolution. Differentiation between these two hypotheses is impossible at the aggregate level, and requires detailed industry data for the most recent period of 1995-98. Without this data, identification problems prevent us from drawing firm conclusions about the sources and implications of the acceleration of TFP in non-IT industries.

2.3 Setting the Speed Limit

WE NOW CONSIDER THE SUSTAINABILITY of recent U.S. growth trends over longer time horizons. Rapid output growth is highly desirable, of course, but cannot continue indefinitely if it is fuelled by a falling unemployment rate and higher labour force participation. Output growth driven by continuing TFP improvements, on the other hand, is more likely to persist. The sustainability of growth has clear implications for government policies. Since economic growth affects tax revenues, potential government expenditures and the long-term viability of programs like Social Security and Medicare, it is closely monitored by government agencies. This section examines the impact of the recent success of the U.S. economy on official growth forecasts.

2.3.1 A Brief Review of Forecast Methodologies

The importance of economic growth for the U.S. government is evident in the considerable effort expended on projecting future growth. No fewer than five government agencies — the Congressional Budget Office (CBO), the Social Security Administration (SSA), the Office of Management and Budget (OMB), the Council of Economic Advisors (CEA), and the General Accounting Office (GAO) — report estimates of future growth for internal use or public discussion. This section briefly discusses the methodologies employed by these agencies.[35]

All forecasts are based on models that rest securely on neoclassical foundations. While the details and assumptions vary, all employ an aggregate production model similar to Equation (1), either explicitly or implicitly. In addition, they all incorporate demographic projections from the SSA as the basic building block for labour supply estimates. The CBO (1995, 1997, 1999a, 1999b, 2000) and the GAO (1995, 1996) employ an aggregate production function and describe the role of labour growth, capital accumulation, and technical progress explicitly. On the other hand, the SSA (1992, 1996), the OMB (1997, 2000), and the CEA (2000) employ a simplified relationship where output growth equals the sum of the growth in hours worked and labour productivity. Projections over longer time horizons are driven by aggregate supply with relatively little attention paid to business cycle fluctuations and aggregate demand effects.

Given the common framework and source data, it is not surprising that the projections are quite similar. Reporting on estimates released in 1997, Stiroh (1998b) finds that the SSA and the GAO projections of per capita GDP in 2025 were virtually identical, while that of the CBO was about 9 percent higher due to economic feedback effects from the improving government budget situation. More recently, the CBO (2000) projects real GDP growth of 2.8 percent and the OMB (2000) projects 2.7 percent for the period 1999-2010, while the CEA (2000) reports 2.8 percent for 1999-2007. Although the timing is slightly different — the CBO projects faster growth than the OMB earlier in the period and the CEA reports projections only through 2007 — the estimates are virtually identical. All three projections identify the recent investment boom as a contributor to rising labour productivity and capital deepening and as a source of continuing economic growth. We now consider the CBO projections in greater detail.

2.3.2 CBO's Growth Projections

The CBO utilizes a sophisticated and detailed, multi-sector growth model of the U.S. economy.[36] The core of this model is a two-factor production function for the non-farm business sector, with CBO projections based on labour force growth, national savings and investment, and exogenous TFP growth. Production function parameters are calibrated to historical data, using a Cobb-Douglas model:

(6) $$Y = A \cdot H^{0.7} \cdot K^{0.3}$$

where Y is potential output, H is potential hours worked, K is capital input, and A is potential total factor productivity.[37]

The CBO projects hours worked on the basis of demographic trends, with separate estimates for different age and sex classifications. These estimates incorporate the SSA estimates of population growth, as well as internal CBO projections of labour force participation and hours worked for the different categories. However, the CBO does not use this demographic detail to identify changes in labour quality. Capital input is measured as the service flow from four types of capital stocks — producers' durable equipment excluding computers, non-residential structures, and inventories. Stocks are estimated by the perpetual inventory method and weighted by rental prices, thereby incorporating some changes in capital quality. TFP growth is projected on the basis of recent historical trends, with labour quality growth implicitly included in CBO's estimate of TFP growth.

Turning to the most recent CBO projections, reported in CBO (2000), we focus on the non-farm business sector, which drives the GDP projections and is based on the most detailed growth model. Table 2.6 summarizes the CBO's growth rate estimates for the 1980s and 1990s, and projections for 1999-2010. We also present estimates from the BLS (2000) and our results.[38] The CBO projects potential GDP growth of 3.1 percent for 1999-2010, up slightly from 3.0 percent in the 1980s and 2.9 percent in the 1990s. The CBO expects actual GDP growth to be somewhat slower at 2.8 percent, as the economy moves to a sustainable, long-run growth rate. Acceleration in potential GDP growth reflects faster capital accumulation and TFP growth, partly offset by slower growth in hours worked. Projected GDP growth is 0.4 percent higher than earlier estimates (CBO, 1999b) due to an upward revision in capital growth (0.1 percent), slightly more rapid growth in hours worked (0.1 percent), and faster TFP growth, reflecting the benchmark revisions of NIPA, and other technical changes (0.2 percent).[39] The CBO's estimates for the non-farm business sector show strong potential output growth of 3.5 percent for 1999-2010. While projected output growth is in line with the experience of the 1990s and somewhat faster than the 1980s, there are significant differences in the underlying sources. Most important, the CBO projects an increasing role for capital accumulation and TFP growth over the next decade, while the growth in the number of hours worked will slow. This implies that future output growth will be driven by ALP growth, rather than the growth in hours worked.

Table 2.6
Growth Rates of Output, Inputs, and Total Factor Productivity, Comparison of the BLS, the CBO, and Jorgenson-Stiroh

	BLS	CBO						Jorgenson-Stiroh	
	Non-farm Business	Overall Economy			Non-farm Business				
	1990-99	1980-90	1990-99	1999-2010	1980-90	1990-99	1999-2010	1980-90	1990-98
Real Output	3.74	3.0	2.9	3.1	3.2	3.4	3.5	3.48	3.55
Labour Input								2.14	2.34
Hours Worked	1.68	1.6	1.2	1.1	1.6	1.5	1.2	1.81	1.76
Labour Quality								0.33	0.58
Capital Input					3.6	3.6	4.4	3.57	3.68
TFP - not adjusted for labour quality					0.9	1.2	1.4	0.91	0.97
TFP - adjusted for labour quality								0.73	0.63
ALP	2.06	1.4	1.7	1.9	1.5	1.9	2.3	1.67	1.79

Note: The CBO estimates refer to "potential" series that are adjusted for business cycle effects. Growth rates do not exactly match those of Table 2.5 since discrete growth rates are used here for consistency with CBO's methodology. Hours worked for CBO Overall Economy refers to potential labour force.

The CBO projects that potential non-farm business ALP growth for 1999-2010 will rise to 2.3 percent, powered by capital deepening (3.2 percent) and TFP growth (1.4 percent). This represents a marked jump in ALP growth, relative to the rate of 1.5 percent recorded in the 1980s and of 1.9 percent recorded in the 1990s. In considering whether the recent acceleration in ALP growth represents a trend break, the CBO "gives considerable weight to the possibility that the experience of the past few years represents such a break (CBO, 2000, p. 43)." This assumption appears plausible given recent events, and low unemployment and high labour force participation make growth in hours worked a less likely source of future growth. Falling investment prices for information technology make capital deepening economically attractive, while the recent acceleration in TFP growth gives further grounds for optimistic projections.

As the investment boom continues and firms substitute more information technology in their production, the CBO has steadily revised its projected growth rates of capital upward. It is worthwhile to note just how much the role of capital accumulation has grown in successive CBO projections, rising from a projected growth rate of 3.6 percent in January 1999 (CBO, 1999a) to 4.1 percent in July 1999 (CBO, 1999b), to 4.4 percent in January 2000 (CBO, 2000). This reflects the inclusion of relatively fast-growing software investment in the benchmark revision of NIPA, but also extrapolates recent investment patterns.

Similarly, the CBO has raised its projected rate of TFP growth in successive estimates — from 1.0 percent in January 1999 to 1.1 percent in July 1999, to 1.4 percent in January 2000.[40] These upward revisions reflect methodological changes in the way the CBO accounts for the rapid price declines in investment, particularly computers, which added 0.2 percent. The CBO adjustments for the benchmark revision of NIPA contributed another 0.1 percent.

Table 2.6 also reports our own estimates of growth for roughly comparable periods. While the time periods are not precisely identical, our results are similar to CBO's. We estimate slightly faster growth during the 1980s, due to rapidly growing consumers' durable services, but slightly lower rates of capital accumulation due to our broader measure of capital. Our growth of hours worked is higher, since we omit the cyclical adjustments made by the CBO to develop their potential series.[41] Finally, our TFP growth rates are considerably lower, due to our labour quality adjustments and inclusion of consumers' durables. If we were to drop the labour quality adjustment, our estimate would rise to 1.0 percent per year from 1990 to 1998, compared to 1.2 percent for the CBO over 1990-99. The remaining difference reflects the fact that we do not include the rapid TFP growth of 1999, but do include the services of consumers' durables, which involve no growth in TFP.

2.3.3 Evaluating the CBO's Projections

Evaluating the CBO's growth projections requires an assessment of their estimates of the growth of capital, labour, and TFP. It is important to emphasize that this is not intended as a criticism of the CBO, but rather a description of "best practice" in the difficult area of growth projections. We also point out that comparisons between our estimates and the CBO's estimates are not exactly due to our broader output concept and our focus on actual data series, as opposed the potential series that are the focus of the CBO.

We begin with the CBO's projections for potential labour input. These data, based on the hours worked from the BLS and SSA demographic projections, show a decline in the growth of hours worked from 1.5 percent in the 1990s to 1.2 percent for the period 1999-2010. This slowdown reflects familiar demographic changes associated with the aging of the U.S. population. However, the CBO does not explicitly estimate labour quality, so that labour composition changes are included in the CBO's estimates of TFP growth and essentially held constant.

We estimate growth in labour quality of 0.57 percent per year for 1990-98, while our projections based on demographic trends yield a growth rate of only 0.32 percent for the 1998-2010 period. Assuming the CBO's labour share of 0.70, this implies a decline in the contribution from labour quality to growth of about 0.18 percentage points per year over CBO's projection horizon. Since this labour quality effect is implicitly incorporated into the CBO's TFP estimates, we conclude that their TFP projections are overstated by this 0.18 percentage points decline in the labour quality contribution.

TFP growth is perhaps the most problematic issue in long-term projections. Based on the recent experience of the U.S. economy, it appears reasonable to expect strong future productivity performance. As discussed above and shown in Table 2.2, TFP growth has increased markedly during the period 1995-98. However, extrapolation of this experience runs the risk of assuming that a temporary productivity spurt is a permanent change in trend.

Second, the recent acceleration of TFP growth is due in considerable part to the surge in productivity growth in IT-producing industries. This makes the economy particularly vulnerable to slowing productivity growth in these industries. Computer prices have declined at extraordinary rates in recent years and it is far from obvious that this can continue. However, acceleration in the rate of decline reflects the change in the product cycle for semi-conductors, which has shifted from three years to two years and may be permanent.

We conclude that the CBO's projection of TFP growth is optimistic in assuming a continuation of recent productivity trends, but nonetheless reasonable. However, we reduce this projection by only 0.18 percent per year to reflect the decline in labour quality growth, resulting in projected TFP growth of 1.22 percent per year. To obtain a projection of labour input growth we add labour quality growth of 0.32 percent per year to the CBO's projection of growth in hours worked of 1.2 percent per year. Multiplying a labour input growth of 1.52 percent per year by the CBO labour share of 0.7, we obtain a contribution of labour input of 1.06 percent.

The CBO's projected annual growth of capital input of 4.4 percent is higher than in any other decade, and 0.8 percent higher than in the 1990s.[42] This projection extrapolates recent increases in the relative importance of computers, software, and communications equipment. Continuing rapid capital accumulation is also predicated on the persistence of high rates of decline in asset prices, resulting from rapid productivity growth in the IT producing sectors. Any attenuation in this rate of decline would produce a double whammy — less TFP growth in IT-producing industries and reduced capital deepening elsewhere.

Relative to historical trends, the CBO's capital input growth projection of 4.4 percent seems out of line with the projected growth of potential output of 3.5 percent. During the 1980s, capital growth exceeded potential output growth by 0.4 percent, according to their estimates, or 0.1 percent in our estimates. In the 1990s, capital growth exceeded output growth by only 0.2 percent, again according to their estimates, and 0.1 percent in our estimates. This difference jumps to 0.9 percent for the period covered by the CBO's projections, that is 1999-2010.

Revising the growth of capital input downward to reflect the difference of 0.2 percent between the growth of output and the growth of capital input during the period 1995-98 would reduce the CBO's projected output growth to 3.35 percent per year. This is the sum of the projected growth of TFP of 1.22 percent per year, the contribution of labour input of 1.06 percent per year, and the contribution of capital input of 1.07 percent per year. This is a very modest reduction in output growth from the CBO's projection of 3.5 percent per year that can be attributed to the omission of a projected decline in labour quality growth.

We conclude that the CBO's projections are consistent with the evidence presented, as well as with our own analysis of recent trends. We must emphasize, however, that any slowdown of the technical progress in information technology could have a major impact on potential growth. Working through both output and input channels, the U.S. economy has become highly dependent on information technology as the driving force behind continued growth. Should productivity growth in these industries falter, the projections we have reviewed could be overly optimistic.

2.4 Industry Productivity

WE HAVE EXPLORED THE SOURCES of U.S. economic growth at the aggregate level and demonstrated that accelerated TFP growth is an important contributor to the recent growth resurgence. Aggregate TFP gains — the ability to produce more output from the same inputs — reflects the evolution of the production structure at the plant or firm level in response to technological changes, managerial choices, and economic shocks. These firm- and industry-level changes then cumulate to determine aggregate TFP growth. We now turn our attention to industry data to trace aggregate TFP growth to its sources in the productivity growth of individual industries, as well as the reallocations of output and inputs among industries.

Our approach utilizes the framework of Jorgenson, Gollop, and Fraumeni (1987) for quantifying the sources of economic growth in U.S. industries. The industry definitions and data sources have been brought up-to-date. The methodology of Jorgenson, Gollop, and Fraumeni for aggregating over industries is based on Domar's (1961) approach to aggregation. Jorgenson and Stiroh (2000) have presented summary data from our work; other recent studies of industry-level productivity growth include BLS (1999), Corrado and Slifman (1999), and Gullickson and Harper (1999). The remainder of this section summarizes our methodology and discusses the results.

2.4.1 Methodology

As with the aggregate production model discussed in Section 2, we begin with an industry-level production model for each industry. A crucial distinction, however, is that industry output Q_i is measured using a "gross output" concept, which includes output sold to final demand as well as output sold to other industries as intermediate goods. Similarly, inputs include all production inputs, including capital services K_i and labour services L_i, as well as intermediate inputs, energy E_i and materials M_i, purchased from other industries.[43] Our model is based on the industry production function:

$$(7) \qquad Q_i = A_i \cdot X_i(K_i, L_i, E_i, M_i)$$

where time subscripts have been suppressed for clarity.

We can derive a growth accounting equation similar to Equation (2) for each industry in order to measure the sources of economic growth for individual industries. The key difference is the use of gross output and an explicit accounting of the contribution to growth of intermediate inputs purchased from other industries. This yields:

$$(8) \qquad \Delta \ln Q_i = \overline{w}_{K_i} \Delta \ln K_i + \overline{w}_{L_i} \Delta \ln L_i + \overline{w}_{E_i} \Delta \ln E_i + \overline{w}_{M_i} \Delta \ln M_i + \Delta \ln A_i$$

where $\overline{w}_i$ is the average share of the subscripted input in the *i*th industry, and the assumptions of constant returns to scale and competitive markets imply that $\overline{w}_{K_i} + \overline{w}_{L_i} + \overline{w}_{E_i} + \overline{w}_{M_i} = 1$.

The augmentation factor $\Delta \ln A_i$ represents the growth in output not explained by input growth and is conceptually analogous to the TFP concept used above in the aggregate accounts. It represents efficiency gains, technological progress, scale economies, and measurement errors that allow more measured gross output to be produced from the same set of measured inputs. We refer to this term as *industry productivity* or simply *productivity* to distinguish it from TFP, which is estimated from a value-added concept of output.[44]

Domar (1961) first developed an internally consistent methodology that linked industry-level productivity growth in Equation (8) with aggregate TFP growth in Equation (2). He showed that aggregate TFP growth can be expressed as a weighted average of industry productivity growth:

(9) $$\Delta \ln A = \sum_{i=1}^{37} \overline{w}_i \cdot \Delta \ln A_i , \quad \overline{w}_i = \frac{1}{2}\left(\frac{P_{i,t} \cdot Q_{i,t}}{P_{Y,t} \cdot Y_t} + \frac{P_{i,t-1} \cdot Q_{i,t-1}}{P_{Y,t-1} \cdot Y_{t-1}} \right)$$

where $\overline{w_i}$ is the "Domar weight", $P_i{\cdot}Q_i$ is current dollar gross output in sector *i*, and $P_Y{\cdot}Y$ is current dollar aggregate value-added. This simplified version of the aggregation formula given by Jorgenson, Gollop, and Fraumeni (1987), excludes re-allocations of value added, capital input, and labour input by sector. Jorgenson and Stiroh (2000) show that these terms are negligible for the period 1958-96, which is consistent with the results of Jorgenson, Gollop, and Fraumeni (1987), and Jorgenson (1990) for periods of similar duration.

Domar weights have the notable feature of not summing up to unity. This reflects the different output concepts used at the aggregate and industry levels in Equations (1) and (7), respectively. At the aggregate level, only primary inputs are included, while both primary and intermediate inputs are included in the industry production functions. For the typical industry, gross output considerably exceeds value added, so the sum of gross output across industries exceeds the sum of value added. This weighting methodology implies that economy-wide TFP growth can grow faster than productivity in any industry, since productivity gains are magnified as they work their way through the production process.[45]

In addition to providing an internally consistent aggregation framework, industry-level gross output allows an explicit role for intermediate goods as a source of industry growth. For example, Triplett (1996) shows that a substantial portion of the price declines in computer output can be traced to steep price declines in semi-conductors, the major intermediate input in the computer-producing industry. Price declines in semi-conductors reflect technological progress — Moore's law in action. This should be measured as productivity growth in the industry that produces semi-conductors. By correctly accounting for the quantity and quality of intermediate inputs, the gross output concept allows aggregate TFP gains to be correctly allocated among industries.

2.4.2 Data Sources

Our primary data include a set of inter-industry transactions accounts developed by the Employment Projections Office of the BLS. The data cover a relatively short time period from 1977 to 1995. We linked the BLS estimates to industry-level estimates back to 1958, described by Stiroh (1998a), and extrapolated to 1996 using current BLS and BEA industry data.[46] This generated a time series from 1958 to 1996 for 37 industries, at roughly the two-digit Standard Industrial Classification (SIC) level, including Private Households and General Government.[47] Table 2.7 lists the 37 industries, the relative size in terms of 1996 value added and gross output, and the underlying SIC codes for each industry.

Before proceeding to the empirical results, we should point out two limitations of this industry-level analysis. Due to the long lag in obtaining detailed inter-industry transactions, investment, and output data by industry, our industry data are not consistent with the BEA benchmark revision of NIPA published in December 1999; they correspond to the NIPA produced by the BEA in November 1997. As a consequence, they are not directly comparable to the aggregate data described in Tables 2.1 through 2.6. Since the impact of the benchmark revision was to raise output and aggregate TFP growth, it is not surprising that the industry data show slower output and productivity growth. In addition, our estimates of rental prices for all assets in this industry analysis are based on the industry-wide asset revaluation terms, as in Stiroh (1998a). They are not directly comparable to the aggregate data on capital input, where asset-specific revaluation terms are included in the rental price estimates. The use of industry-wide revaluation terms tends to reduce the growth in capital services since assets with falling relative prices, such as computers, have large service prices and rapid accumulation rates.

Table 2.7
1996 Value Added and Gross Output by Industry

Industry	SIC Codes	Value Added	Gross Output
Agriculture	01-02, 07-09	133.3	292.2
Metal Mining	10	8.8	10.7
Coal Mining	11-12	14.7	21.1
Petroleum and Gas	13	57.4	83.3
Non-metallic Mining	14	10.5	17.0
Construction	15-17	336.0	685.5
Food Products	20	147.2	447.6
Tobacco Products	21	26.7	32.7
Textile Mill Products	22	19.9	58.9
Apparel and Textiles	23	40.7	98.5
Lumber and Wood	24	34.2	106.7
Furniture and Fixtures	25	23.4	54.5
Paper Products	26	68.3	161.0
Printing and Publishing	27	113.5	195.6
Chemical Products	28	184.0	371.2
Petroleum Refining	29	44.7	184.3
Rubber and Plastic	30	64.1	148.9
Leather Products	31	3.4	8.1
Stone, Clay, and Glass	32	40.4	79.1
Primary Metals	33	57.6	182.1
Fabricated Metals	34	98.4	208.8
Industrial Machinery and Equipment	35	177.8	370.5
Electronic and Electric Equipment	36	161.9	320.4
Motor Vehicles	371	84.9	341.6
Other Transportation Equipment	372-379	68.0	143.8
Instruments	38	81.3	150.0
Miscellaneous Manufacturing	39	24.8	49.3
Transport and Warehouse	40-47	258.6	487.7
Electric Utilities	491, 493	111.8	186.7
Gas Utilities	492, 493, 496	32.9	57.9
Trade	50-59	1,201.2	1,606.4
FIRE	60-67	857.8	1,405.1
Services	70-87, 494-495	1,551.9	2,542.8
Government Enterprises		95.2	220.2
Private Households	88	1,248.4	1,248.4
General Government		1,028.1	1,028.1

Note: All values are in current dollars. Value added refers to payments to capital and labour. Gross output includes payments for intermediate inputs.

2.4.3 Empirical Results

2.4.3.a Sources of Industry Growth

Table 2.8 reports estimates of the components of Equation (8) for the period 1958-96. For each industry, we show output growth, the contribution of each input (defined as the nominal share-weighted growth rate of the input), and productivity growth. We also report average labour productivity (ALP) growth, defined as real gross output per hour worked, and the Domar weights calculated from Equation (9). We focus the discussion of our results on industry productivity and ALP growth.

Industry productivity growth was the highest in two high-tech industries, Industrial Machinery and Equipment, and Electronic and Electric Equipment, at 1.5 percent and 2.0 percent per year, respectively. Industrial Machinery includes the production of computer equipment (SIC no. 357) and Electronic Equipment includes the production of semi-conductors (SIC no. 3674) and communications equipment (SIC no. 366). The enormous technological progress in the production of these high-tech capital goods has generated falling prices and productivity growth, and fuelled the substitution towards information technology.

An important feature of the data is that productivity growth can be isolated for industries that produce intermediate goods, for example, Electronic and Electric Equipment.[48] Consider the contrast between computer production and semi-conductor production. Computers are part of final demand, sold as consumption and investment goods, and can be identified in the aggregate data, as was done in Table 2.2. Semi-conductors, on the other hand, do not appear at the aggregate level, since they are sold almost entirely as an input to computers, telecommunications equipment, and an increasingly broad range of other products such as machine tools, automobiles, and virtually all recent vintages of appliances. Nonetheless, improved semi-conductor production is an important source of aggregate TFP growth since it is ultimately responsible for the lower prices and improved quality of goods like computers produced for final demand.

The enormous price declines in computer equipment and the prominent role of investment in computers in the GDP accounts have led Gordon (1999b), Whelan (1999), and others to emphasize technological progress in the production of computers. Triplett (1996), however, quantifies the role of semi-conductors as an intermediate input and estimates that falling semi-conductor prices may account for virtually all of the relative price decline in computer equipment. He concludes, "productivity in the computer industry palls beside the enormous increases in productivity in the semi-conductor industry (Triplett, 1996, p. 137)."[49]

The decline in the prices of semi-conductors is reflected in the prices of intermediate input into the computer industry, effectively moving productivity away from computers and toward semi-conductor production. Building on this observation, Oliner and Sichel (2000) present a model that includes 3 sectors — semi-conductor production, computer production, and other goods — and shows that productivity in the semi-conductors sector is substantially more important than productivity in the computer sector. Our complete industry framework with Domar aggregation over all industries captures the contributions of productivity growth from all industries.

The impact of intermediate inputs can be seen in Table 2.8 in the large contribution of material inputs in the Industrial Machinery industry. Since a substantial portion of these inputs consists of semi-conductors purchased from the Electronic Equipment industry, productivity gains that lower the prices of semi-conductors increase the flow of intermediate inputs into the Industrial Machinery industry. By correctly accounting for these inputs, industry productivity growth in the Industrial Machinery industry falls, and we can rightly allocate technological progress to the Electronic Equipment industry, which produces semi-conductors. While this type of industry reallocation does not affect aggregate productivity growth, it is important to identify the sources of productivity growth and allocate the latter among industries in order to assess the sustainability of the recent acceleration in productivity.

The two high-tech industries also show high rates of average labour productivity (ALP) growth, respectively 3.1 and 4.1 percent per year. This reflects an underlying relationship similar to Equation (3) for the aggregate data, where industry ALP growth reflects industry productivity growth, labour quality growth, and increases in input intensity, including increases in capital as well as intermediate inputs per hour worked. As implied by Table 2.8, these industries showed rapid accumulation of capital and intermediate inputs, which raised ALP growth above productivity growth. It is also worthwhile to note that Communications, another high-tech industry, shows an ALP growth much faster than industry productivity growth due to the rapid accumulation of inputs, notably intermediate materials. These results highlight the crucial importance of accounting for all inputs when examining the sources of industry growth.

Table 2.8
Sources of U.S. Economic Growth by Industry, 1958-96

Industry	Output Growth	Contributions of Inputs				Productivity Growth	ALP Growth	Domar Weight
		Capital	Labour	Energy	Materials			
Agriculture	1.70	0.19	-0.13	-0.04	0.51	1.17	3.21	0.062
Metal Mining	0.78	0.73	-0.07	-0.07	-0.26	0.44	0.99	0.003
Coal Mining	2.35	0.82	0.00	0.06	0.63	0.84	2.32	0.005
Petroleum and Gas	0.43	0.61	-0.01	0.06	0.20	-0.44	0.88	0.022
Non-metallic Mining	1.62	0.59	0.18	0.06	0.34	0.46	1.52	0.003
Construction	1.43	0.07	0.87	0.02	0.91	-0.44	-0.38	0.113
Food Products	2.20	0.21	0.18	0.00	1.27	0.54	1.59	0.076
Tobacco Products	0.43	0.59	0.05	0.00	-0.01	-0.20	0.88	0.004
Textile Mill Products	2.23	0.12	0.02	0.01	0.86	1.23	2.54	0.013
Apparel and Textiles	2.03	0.24	0.17	0.00	0.82	0.80	2.01	0.022
Lumber and Wood	2.24	0.21	0.33	0.02	1.70	-0.02	1.55	0.015
Furniture and Fixtures	2.91	0.31	0.58	0.02	1.44	0.56	1.78	0.007
Paper Products	2.89	0.50	0.40	0.05	1.51	0.42	1.96	0.022
Printing and Publishing	2.51	0.55	1.20	0.02	1.19	-0.44	0.14	0.024
Chemical Products	3.47	0.74	0.47	0.09	1.58	0.58	2.02	0.048
Petroleum Refining	2.21	0.44	0.24	0.49	0.71	0.33	0.80	0.033
Rubber and Plastic	5.17	0.47	1.16	0.08	2.43	1.04	1.94	0.016
Leather Products	-2.06	-0.11	-1.13	-0.02	-1.08	0.28	2.08	0.004
Stone, Clay, and Glass	1.86	0.26	0.37	0.00	0.82	0.41	1.30	0.014
Primary Metals	1.14	0.13	0.05	-0.03	0.77	0.22	1.51	0.040

Table 2.8 (cont'd)

Industry	Output Growth	Contributions of Inputs				Productivity Growth	ALP Growth	Domar Weight
		Capital	Labour	Energy	Materials			
Fabricated Metals	2.28	0.26	0.28	0.00	1.09	0.65	1.88	0.035
Industrial Machinery and Equipment	4.79	0.52	0.75	0.02	2.04	1.46	3.15	0.048
Electronic and Electric Equipment	5.46	0.76	0.65	0.03	2.04	1.98	4.08	0.036
Motor Vehicles	3.61	0.28	0.29	0.02	2.78	0.24	2.28	0.043
Other Transportation Equipment	1.31	0.23	0.37	0.00	0.52	0.18	1.00	0.027
Instruments	5.23	0.65	1.44	0.03	1.99	1.12	2.57	0.017
Miscellaneous Manufacturing	2.53	0.34	0.41	0.00	0.95	0.82	2.08	0.008
Transport and Warehouse	3.25	0.20	0.72	0.12	1.34	0.86	1.74	0.061
Communications	5.00	1.62	0.53	0.02	1.95	0.88	3.93	0.033
Electric Utilities	3.22	1.01	0.20	0.67	0.83	0.51	2.52	0.026
Gas Utilities	0.56	0.66	-0.04	0.14	0.05	-0.24	0.94	0.016
Trade	3.66	0.62	0.83	0.04	1.19	0.98	2.49	0.195
FIRE	3.42	1.14	0.94	0.00	1.52	-0.18	0.66	0.131
Services	4.34	0.84	1.70	0.07	1.92	-0.19	0.92	0.208
Government Enterprises	2.86	1.24	1.08	0.23	0.83	-0.52	0.49	0.022
Private Households	3.50	3.55	-0.06	0.00	0.00	0.00	5.98	0.137
General Government	1.35	0.60	0.75	0.00	0.00	0.00	0.46	0.131

Note: Output growth is the average annual growth in real gross output. The contributions of inputs are defined as the average, share-weighted growth of the individual input. Productivity growth is defined in Equation (8). ALP growth is the growth in average labour productivity. The Domar weight is the average ratio of industry gross output to aggregate value added, as defined in Equation (9). All numbers except Domar weights are percentages.

Productivity growth in information technology provides a final perspective on the conclusions of Greenwood, Hercowitz, and Krusell (1997), and Hercowitz (1998). They argue that some 60 percent of post-war U.S. growth can be attributed to investment-specific (embodied) productivity growth, which they distinguish from input accumulation and (disembodied) productivity growth. They note that the relative price of equipment in the United States has fallen 3 percent per year, which they interpret as evidence of technical change that affects capital goods, but not consumption goods. Our decomposition, however, reveals that declines in the prices of investment goods are the consequence of improvements in industry (disembodied) productivity. The Domar aggregation shows how these improvements contribute directly to aggregate TFP growth. There is no separate role for investment-specific technical change.

Other industries that show relatively strong productivity growth include Agriculture, Textile Mill Products, Rubber and Plastic, Instruments, and Trade. All of these industries recorded productivity growth in the 1.0 percent per year range, and ALP growth in the 2 to 3 percent range. Industries with the slowest productivity growth include Petroleum and Gas, Construction, Printing and Publishing, and Government Enterprises, all of which showed a decline in productivity of nearly 0.5 percent per year.

It is worth emphasizing that 9 industries showed negative productivity growth over the entire period, a counter-intuitive result if we were to interpret productivity growth solely as technological progress. It is difficult to envision technology steadily worsening for a period of nearly 40 years as implied by these estimates. The perplexing phenomenon of negative technical progress was a primary motivation for the work of Corrado and Slifman (1999), and Gullickson and Harper (1999), who suggest persistent measurement problems as a plausible explanation. Corrado and Slifman (1999) conclude, "a more likely statistical explanation for the implausible productivity, profitability, and price trends… is that they reflect problems in measuring prices (p. 331)." If prices are systematically overstated because quality change is not accurately measured, then output and productivity are correspondingly understated. We do not pursue this idea here, but simply point out that measurement problems are considered a reasonable explanation by some statistical agencies.[50]

An alternative interpretation for negative productivity growth is the possibility of declines in efficiency that have no association with technology. These might include lower quality of management and a worsening of industrial organization as barriers to entry are raised. This appears to be a plausible explanation, given the widespread occurrence of negative productivity growth for extended periods of time. Until more careful research linking firm- and plant-level productivity to industry productivity estimates has been done, it would be premature to leap to the conclusion that estimates of economic performance should be adjusted so as to eliminate negative productivity growth rates, wherever they occur.

Low productivity growth rates are surprising in light of the fact that many of the affected industries are heavy investors in information technology. Stiroh (1998a), for example, reports that nearly 80 percent of computer investment in the early 1990s was in three service-related industries: Trade, FIRE, and Services. Triplett (1999) reports a high concentration in service industries using the BEA's capital use survey. The apparent combination of slow productivity growth and heavy computer-use remains an important obstacle for new economy proponents who argue that the use of information technology is fundamentally changing business practices and raising productivity throughout the U.S. economy.

2.4.3.b Comparison with Other Results

Before proceeding to the Domar aggregation results, it is useful to compare these results to those of three other recent studies — BLS (1999), Corrado and Slifman (1999), and Gullickson and Harper (1999). BLS (1999) reports industry productivity growth ("industry multifactor productivity" in their terminology) for 19 manufacturing industries over 1949-96. Corrado and Slifman (1999) report estimates of ALP growth for selected one- and two-digit SIC industries over the period 1977-97. Gullickson and Harper (1999) report industry productivity growth for certain one- and two-digit SIC industries based on two output series for the period 1947-92. Similar to BLS (1999), Gullickson and Harper use a "sectoral output" concept estimated by the Employment Projections staff at the BLS; also, for 1977-92, they use the BEA's gross output series, "adjusted for consistency."[51] Note that none of these studies reflect the BEA benchmark revision of NIPA.

Differences in time periods, industry classifications, and methodologies make a definitive reconciliation with our results impossible. For example, the BLS (1999) reports detailed manufacturing industries; Corrado and Slifman (1999) use a value-added concept, the BEA's "gross product originating," for output; Gullickson and Harper (1999) use the same data sources as we do, but make different adjustments for consistency and do not account for labour quality growth. Nonetheless, it is useful to compare broad trends over similar time periods to assess the robustness of our findings.

We first consider the ALP estimates produced by Corrado and Slifman (1999). We can compare similar time periods, but there are relatively few overlapping industries since our industry breakdown focuses on manufacturing industries, while they provide details primarily for service industries. For comparable industries, however, the results are quite similar. For 7 industries with comparable definitions, 5 show differences in ALP growth of less than 0.25 percent when we compare our estimates for 1977-96 to Corrado and Slifman's estimates for 1977-97 (Corrado and Slifman, 1999, Table 2.2).[52] Our ALP growth rates for Communication and Trade are below theirs by 1.3 percent and 0.4 percent, respectively, for these periods.

For the majority of industries, our productivity estimates for 1977-92 are similar to those of Gullickson and Harper (1999). The range of discrepancies is somewhat greater due to the difficulty of linking the various data sets needed to estimate intermediate inputs and industry productivity growth. For 7 of the 11 comparable industries, productivity differences are below 0.5 percent, while we found larger discrepancies for Metal Mining, Coal Mining, Petroleum and Gas, and Services.[53] Similar differences can also be seen in Gullickson and Harper's comparison of productivity growth estimated from the BLS and BEA gross output series, where they find differences of 0.5 percentage points or more in 17 out of 40 industries and aggregates. Methodological differences, such as the inclusion of labour quality growth in our estimates of labour input growth, contribute to this divergence, as do different methods of linking data sets.

Neither Corrado and Slifman (1999) nor Gullickson and Harper (1999) break out ALP growth or industry productivity growth among detailed manufacturing industries. To gauge these results, we have compared our manufacturing results to the manufacturing industry estimates produced by the BLS (1999). For the 18 industries that are comparable, 10 showed productivity differences of less than 0.25 percent for 1979-96; 2 showed differences varying between 0.25 percent and 0.5 percent; the remaining 6 industries, Textile

Mills, Lumber and Wood, Petroleum Refining, Leather, Stone, Clay and Glass, and Instruments, showed differences greater than 0.5 percent.[54]

2.4.3.c Domar Aggregation

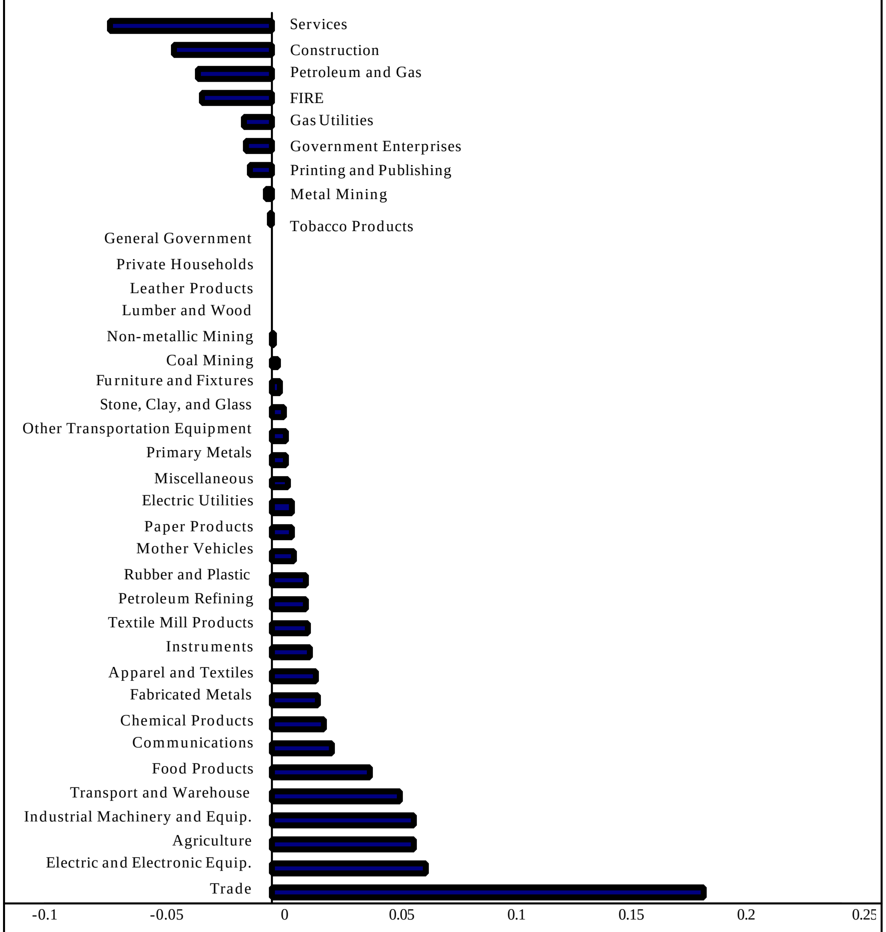
We now turn to the aggregation of industry productivity growth described by Equation (9). This is not directly comparable to our estimates of aggregate productivity, due to different vintages of data and a broader definition of output. Nonetheless, it is useful to quantify an industry's contribution to aggregate TFP growth and to trace aggregate productivity growth back to its sources at the level of the individual industry. These results update the earlier estimates of Jorgenson, Gollop, and Fraumeni (1987). Gordon (1999b) presents a similar decomposition of ALP growth, although he focuses exclusively on the contribution of computer production.

Figure 2.11 presents our estimates of each industry's contribution to aggregate TFP growth for the period 1958-96. This follows Equation (9) by weighting industry productivity growth by the "Domar weight," defined as industry gross output divided by aggregate value added. Summing across industries gives an estimate of aggregate TFP growth of 0.48 for 1958-96. This is lower than the number implied by Table 2.2 for two reasons. First, the data are prior to the BEA benchmark revision, which raised output and TFP growth. Second, the estimates reflect a broader output concept that includes Government Enterprises, which we estimate as having negative industry productivity growth, and General Government, which has zero productivity growth by definition. The estimate is consistent, however, with the estimates produced by Ho, Jorgenson, and Stiroh (1999), and Jorgenson and Stiroh (1999), which are based on the same vintage of data.

The most striking feature of Figure 2.11 is the wide range of industry contributions. Trade, Industrial Machinery, and Electronic Equipment make the largest contributions, although for different reasons. Trade has solid, but not exceptionally strong productivity growth of almost 1 percent per year; it makes the largest contribution due to its large relative size. Trade receives a Domar weight of nearly 0.20. Industrial Machinery and Electronic Equipment, on the other hand, make important contributions due to their rapid productivity growth, 1.5 percent and 2.0 percent, respectively, in spite of their relative small size, with Domar weights of 0.05 and 0.04, respectively. The contribution of an industry to aggregate productivity growth depends on both productivity performance and relative size.

Figure 2.11

Industry Contributions to Aggregate Total Factor Productivity Growth, 1958-96



Note: Each industry's contribution is calculated as the product of industry productivity growth and the industry Domar weight, averaged for 1958-96.

Figure 2.11 also highlights the impact of the 9 industries that experienced negative productivity growth over this period. Again, both performance and relative size matter. The Services industry makes a negative contribution of 0.07 due to its large weight and productivity growth of –0.19 percent. Construction, on the other hand, shows even slower industry productivity growth, –0.44 percent per year, but makes a smaller negative contribution, since it is much smaller than Services. We can also do a "thought experiment" similar to Corrado and Slifman (1999) and Gullickson and Harper (1999), and imagine that productivity growth is zero in these 9 industries rather than negative. By zeroing out the negative contributions, we find that aggregate TFP growth would have been 0.22 percent higher, an increase of nearly half.[55] Clearly, negative productivity growth in these industries is an important part of the aggregate productivity story.

Finally, these data enable us to provide some new perspective on an argument made by Gordon (1999b), who decomposes trend-adjusted ALP growth into a portion due to computer production and a residual portion for the rest of the economy.[56] He finds that the former accounts for virtually all of the productivity acceleration since 1997. While we cannot comment directly on his empirical estimates since our industry data end in 1996 and we examine TFP growth rather than ALP growth, we can point to an important qualification to his argument. The U.S. economy is made up of industries with both positive and negative productivity growth rates, so that comparing one industry to the aggregate of all others necessarily involves aggregation over off-setting productivity trends. The fact that this aggregate does not show net productivity growth does not entail the absence of gains in productivity in any of the component industries, since such gains could be offset by declines in other industries.

Consider our results for 1958-96 and the importance of the negative contributions. The 5 industries with the largest, positive contributions — Trade, Electronic Equipment, Agriculture, Industrial Machinery, and Transport — cumulatively account for a sum across all industries of about 0.5 percent per year. Nonetheless, we find sizeable productivity growth in some of the remaining industries that are offset by negative contributions in others. This logic and the prevalence of negative productivity growth rates at the industry level, in BLS (1999), Corrado and Slifman (1999), and Gullickson and Harper (1999), suggest that a similar argument could hold for ALP and for the most recent period. This raises the question of whether off-setting productivity growth rates are responsible for Gordon's finding that there is "no productivity growth in the 99 percent of the economy located outside the sector which manufactures computer hardware (Gordon, 1999b, p. 1)." Assessing the breadth of recent productivity gains and identifying the sources of productivity growth at the industry level remains an important task for future research.

2.5 Conclusion

THE PERFORMANCE OF THE U.S. ECONOMY in the late 1990s has been nothing short of phenomenal. After a quarter century of economic malaise, accelerating total factor productivity growth and capital deepening have led to a remarkable growth resurgence. The pessimism of the famous Solow (1987) paradox, that we see computers everywhere but in the productivity statistics, has given way to optimism about the information age. Productivity statistics, beginning in 1995, have begun to reveal a clearly discernible impact of information technology. Both labour productivity and TFP growth have jumped to rates not seen for such an extended period of time since the 1960s. While a substantial portion of these gains can be attributed to computers, there is growing evidence of similar contributions from software and communications equipment — each equal in importance to computers.

The forces shaping the information economy originate in the rapid progress of semi-conductor technology — Moore's Law at work. These gains are driving down the relative prices of computers, software, and communications equipment, and inducing massive investments in these assets by firms and households. Technological progress and the induced capital deepening are the primary factors behind accelerating output growth in recent years. The sustainability of recent growth trends, therefore, hinges to a large degree on the prospects for continuing progress, especially in the production of semiconductors. While this seems plausible, perhaps even likely, the contribution of high-tech assets to the stronger growth remains subject to considerable uncertainty, owing to incomplete information on the price trends of these assets.

The vibrant performance of the U.S. economy has not gone unnoticed. Forecasters have had to raise their projected growth rates, and raise them again. The moderate speed limits set by Blinder (1997) and Krugman (1997), reflecting the best evidence available only a few years ago, have given way to the optimism of the ordinarily conservative community of official forecasters.

Our review of the evidence now available suggests that the official forecasters are relying very heavily on a continuation of the acceleration in U.S. economic growth since 1995.

What are the risks associated with the optimistic view of future U.S. economic growth in the information age? Upward revision of growth projections seems a reasonable response as evidence accumulates of a possible break in trend productivity growth. Nonetheless, caution is warranted until productivity patterns have been observed for a longer time period. Should the pace of technological progress in high-tech industries diminish, economic growth would take a double hit— slower total factor productivity growth in key industries that produce high-tech equipment and slower capital accumulation in others that invest in and use high-tech equipment. Both factors have made important contributions to the recent success of the U.S. economy, so that any slowdown would reduce future growth potential.

At the same time, we must emphasize that the uncertainty surrounding intermediate-term projections has become much greater as a consequence of widening gaps in our knowledge, rather than changes in the volatility of economic activity. The excellent research that underlies estimates of prices and quantities of computer investment in NIPA has provided much needed illumination of the impact of information technology. But this is only part of the contribution of information technology to economic growth and, in fact, may not be the largest. As the role of technology continues to increase, ignorance of the most basic empirical facts about the information economy will plague researchers as well as forecasters. The uncertainties about past and future economic growth will not be resolved quickly. This is, of course, a guarantee that the lively economic debate now unfolding will continue for the foreseeable future.

The first priority for empirical research must be the construction of constant-quality price indices for a wider variety of high-tech assets. These assets are becoming increasingly important in the U.S. economy, but only a small portion have constant-quality price deflators that can translate the improved production characteristics into accurate measures of investment and output. This echoes the earlier findings of Gordon (1990), who reported that official price measures substantially overstate price changes for capital goods. In fact, Gordon identified computers and communications equipment as two assets with the largest overstatements, together with aircraft, which we have not included.[57] Much remains to be done to complete Gordon's program aimed at implementing constant-quality price deflators for all components of investment in NIPA.

The second priority for research is to decompose the sources of economic growth at the industry level. Fortunately, the required methodology is well established and increasingly familiar. Domar aggregation over industries underlies the back-of-the-envelope calculations of the contribution of information technology to economic growth outlined in Section 3, as well as the more careful and comprehensive view of the contributions of industry-level productivity that we have presented in Section 4. This view will require considerable refinement to discriminate among alternative perspectives on the rapidly unfolding information economy. However, the evidence already available is informative on the most important issue. This is the "new economy" view that the impact of information technology is like *phlogiston*, an invisible substance that spills over in every kind of economic activity and reveals its presence by increases in industry-level productivity growth across the U.S. economy. This view is simply inconsistent with the empirical evidence.

Our results suggest that while technology is clearly the driving force in the resurgence of growth, familiar economic principles can be applied. Productivity growth in the production of information technology is responsible for a sizeable part of the recent spurt in TFP growth and can be identified with price declines for high-tech assets and semi-conductors. This has induced an eruption of investment in these assets that is responsible for capital deepening in the industries that use information technology. Information technology provides a dramatic illustration of economic incentives at work! However, there is no corresponding eruption of industry-level productivity growth in these sectors that would herald the arrival of phlogiston-like spillovers from production in the information technology industries.

Many of the goods and services produced with high-tech capital may not be adequately measured, as suggested in the already classic paper of Griliches (1994). This may help to explain the surprisingly low productivity growth in many of the high-tech intensive, service industries. If the official data are understating both real investment in high-tech assets and the real consumption of commodities produced with these assets, the under-estimation of U.S. economic performance may be far more serious than we have suggested. Only as the statistical agencies continue their slow progress towards improved data and implementation of state-of-the-art methodology will this murky picture become more transparent.

Notes

1 Labour productivity growth in the business sector averaged 2.7 percent over 1995-99, the four fastest annual growth rates in the 1990s, except for a temporary jump of 4.3 percent in 1992 as the economy exited recession (BLS, 2000).

2 Stiroh (1999) critiques alternative new economy views; Triplett (1999) examines data issues in the new economy debate; and Gordon (1999b) provides an often-cited rebuttal of the new economy thesis.

3 Our work on computers builds on the path-breaking research of Oliner and Sichel (1994, 2000), Sichel (1997, 1999), and our own earlier results, reported in Jorgenson and Stiroh (1995, 1999, 2000), and Stiroh (1998a). Other valuable work on computers includes Haimowitz (1998), Kiley (1999), and Whelan (1999). Gordon (1999a) provides a historical perspective on the sources of U.S. economic growth, and Brynjolfsson and Yang (1996) review the micro evidence on computers and productivity.

4 See Baily and Gordon (1988), Stiroh (1998a), Jorgenson and Stiroh (1999), and Department of Commerce (1999) for earlier discussions of relative price changes and input substitution in the high-tech sectors.

5 BLS (2000) estimates for the business sector show a similar increase from 1.6 percent over 1990-95 to 2.6 percent over 1995-98. See CEA (2000, p. 35) for a comparison of productivity growth at various points in the economic expansions of the 1960s, 1980s, and 1990s.

6 See Gullickson and Harper (1999), Jorgenson and Stiroh (2000), and Section 4, below, for industry-level analyses.

7 There is no consensus, however, on the fact that technical progress in computer and semi-conductor production is slowing. According to Fisher (2000), chip processing speed continues to increase rapidly. Moreover, the product cycle is accelerating as new processors are brought to market more quickly.

8 See Dean (1999) and Gullickson and Harper (1999) for the BLS perspective on measurement errors; Triplett and Bosworth (2000) provide an overview of the measurement of output in the service industries.

9 It would be a straightforward change to make technology labour-augmenting or "Harrod-neutral," so that the production possibility frontier could be written: $Y(I, C) = X(K, AL)$. Also, there is no need to assume that inputs and outputs are separable, but this simplifies our notation.

10 Baily and Gordon (1988), Griliches (1992), Stiroh (1998a), Jorgenson and Stiroh (1999), Whelan (1999), and Oliner and Sichel (2000) discuss the impact of investment in computers from these two perspectives.

11 Triplett (1996) points out that much of the decline in computer prices reflects falling semi-conductor prices. If all inputs are correctly measured for quality change, therefore, much of the TFP gains in computer production are rightly pushed back to TFP gains in semi-conductor production since semi-conductors are a major intermediate input in the production of computers. See Flamm (1993) for early estimates of semi-conductor prices. We address this question further in Section 4.

12 See Appendix A for details on our source data and methodology for estimating output.

13 Current dollar NIPA GDP in 1998 was $8,759.9B. Our estimate of $8,013B differs due to total imputations ($740B), exclusion of general government and government enterprise sectors ($972B and $128B, respectively), and exclusion of certain retail taxes ($376B).

14 See Appendix B for details on the theory, source data, and methodology for estimating capital services.

15 Jorgenson (1996) provides a recent discussion of our model of capital as a factor of production. The BLS (1983) describes the version of this model employed in the official productivity statistics. Hulten (2000) provides a review of the specific features of this methodology for measuring capital input and the link to economic theory.

16 More precisely, growth in capital quality is defined as the difference between the growth in capital services and the growth in the average of the current and lagged stock of capital. Appendix B provides further details. We use a geometric depreciation rate for all reproducible assets, so that our estimates are not identical to the wealth estimates published by the BEA (1998b).

17 Tevlin and Whelan (1999) provide empirical support for this explanation, reporting that computer investment is particularly sensitive to the cost of capital, so that the rapid drop in service prices can be expected to trigger a large investment response.

18 An econometric model of the responsiveness of different types of capital services to own- and cross-price effects could be used to test for complementarity, but this is beyond the scope of the paper.

19 According to Parker and Grimm (2000), the total software investment of \$123.4B includes \$35.7B in pre-packaged software, \$42.3B in custom software, and \$45.4B in own-account software in 1998. Applying the weighting conventions employed by the BEA, this implies that \$46.3B = \$35.7B + 0.25 * \$42.3B, or 38 percent of the total software investment, is deflated with explicit quality adjustments.

20 Grimm (1997) presents hedonic estimates for digital telephone switches and reports average price declines of more than 10 percent per year from 1985 to 1996.

21 Appendix C provides details on the source data and methodology.

22 By comparison, the BLS (2000) reports growth in business hours of 1.2 percent over 1990-95 and 2.3 percent over 1995-98. The slight discrepancies reflect our methods of estimating hours worked by the self-employed, as well as minor differences in the scope of our output measures.

23 Note that we have broken broadly defined capital into tangible capital services, *K*, and consumers' durables services, *D*.

24 Table 2.2 also presents preliminary results for the more recent period of 1995-99, where the 1999 values are based on the estimation procedure described in the Annex to this chapter, rather than on the detailed model described above. The results for 1995-98 and 1995-99 are quite similar; we focus our discussion on the period 1995-98.

25 See Katz and Krueger (1999) for explanations of the strong performance of the U.S. labour market, including demographic shifts toward a more mature labour force, a rise in the prison age population, improved efficiency of labour markets, and the "weak backbone hypothesis" of worker restraint.

26 We are indebted to Dan Sichel for very helpful discussions of this timing convention.

27 Oliner and Sichel (2000) provide a detailed comparison of the results across several studies of computers and economic growth.

28 See Krugman (1997) and Blinder (1997) for a discussion of the usefulness of this relationship.

29 The BLS (2000) shows similar trends for the business sector with the growth in hours worked increasing from 1.2 percent during 1990-95 to 2.3 percent during 1995-98, while ALP increased from 1.58 percent to 2.63 percent.

30 The notion that official price deflators for investment goods omit substantial quality improvements is hardly novel. The magisterial work of Gordon (1990) successfully quantified the overstatements of inflation rates in the prices of a wide array of investment goods, covering all producers' durable equipment in the NIPA.

31 This point was originally made by Jorgenson (1966); Hulten (2000) provides a recent review.

32 Gordon (1999a), Stiroh (1998a), and Whelan (1999) also provide estimates.

33 This calculation shows that the simplified model of Oliner and Sichel (2000) is a special case of the complete Domar weighting scheme used in Section 4.

34 Relative price changes in the Base case are taken from the investment prices presented in Table 2.5. Output shares are estimated based on final demand sales available from the BEA website for computers and from Parker and Grimm (2000) for software. Investment in communications equipment is from the NIPA, and we estimate other final demand components for communications equipment using ratios relative to final demand for computers. This is an approximation necessitated by the lack of complete data on final demand sales by commodity.

35 Stiroh (1998b) provides details and references to supporting documents.

36 The 5 sectors — non-farm business, farm, government, residential housing, and households, and non-profit institutions — follow the breakdown used in Table 1.7 of the NIPA.

37 See CBO (1995, 1997) for details on the underlying model and the adjustments for business cycle effects that lead to the potential series.

38 Note that the growth rates in Table 2.6 do not exactly match those of Table 2.2 due to differences in calculating growth rates. All growth rates in Table 2.6 follow the CBO's convention of calculating discrete growth rates as $g = [(X_t / X_0)^{1/t} - 1]*100$, while growth rates in Table 2.2 are calculated as $g = [\ln(X_t / X_0) / t]*100$.

39 See CBO (2000, p. 25 and p. 43) for details.

40 Earlier upward revisions to TFP growth primarily reflect "technical adjustment… for methodological changes to various price indices" and "increased TFP projections (CBO, 1999b, p. 3)."

41 See CBO (1995) for details on the methodology used for cyclical adjustments to derive the "potential" series.

42 These comparisons are from CBO (2000, Table 2-6).

43 This is analogous to the sectoral output concept used by the BLS. See Gullickson and Harper (1999), particularly pp. 49-53, for a review of the concepts and terminology used by the BLS.

44 The BLS refers to this concept as *multi-factor productivity* (MFP).

45 Jorgenson, Gollop, and Fraumeni (1987), particularly Chapter 2, provide details and earlier references; Gullickson and Harper (1999, p. 50) discuss how aggregate productivity can exceed industry productivity in the Domar weighting scheme.

46 We are grateful to Mun Ho for his extensive contribution to the construction of the industry data.

47 Appendix D provides details on the component data sources and linking procedures.

48 Our industry classification is too broad to isolate the role of semi-conductors.

49 This conclusion rests critically on the input share of semi-conductors in the computer industry. Triplett reports Census data estimates placing this share at 15 percent for 1978-94, but states that industry sources estimate this share to be closer to 45 percent. This has an important impact on his results. At one end of the spectrum, if no account is made for semi-conductor price declines, the relative productivity in computer equipment increases 9.1 percent over 1978-94. Assuming a 15 percent share for semi-conductors reduces this value to 9 percent; assuming a 45 percent share reduces it to 1 percent.

50 Dean (1999) summarizes the BLS view on this issue. McGuckin and Stiroh (2000) attempt to quantify the magnitude of the potential mismeasurement effects.

51 See Gullickson and Harper (1999), particularly pp. 55-56, for details.

52 These 5 industries are Agriculture, Construction, Transportation, FIRE and Services. Note that our estimates for 1977-1996 are not shown in Table 2.10.

53 The 7 other industries that are comparable are Agriculture, Non-metallic Mining, Construction, Transportation, Communications, Trade, and FIRE.

54 The 10 industries with small differences are Food Products, Apparel, Furniture and Fixtures, Paper Products, Printing and Publishing, Chemical Products, Primary Metals, Industrial and Commercial Machinery, Electronic and Electric Machinery, and Miscellaneous Manufacturing. The 2 industries with slightly larger differences are Rubber and Plastic, and Fabricated Metals.

55 This aggregate impact is smaller than that estimated by Gullickson and Harper (1999), partly because our shares differ due to the inclusion of a Household and Government industry. Also, as pointed out by Gullickson and Harper, a complete re-estimation would account for the change in intermediate inputs implied by the productivity adjustments.

56 Oliner and Sichel (2000) argue that Gordon's conclusion is weakened by the new NIPA data released in the benchmark revision, which allow a larger role for ALP growth outside of computer production.

57 Gordon (1990), Table 12.3, p. 539.

Annex:
Extrapolation for 1999

Table 2.2 presents primary growth accounting results through 1998 and preliminary estimates for 1999. The data through 1998 are based on the detailed methodology described in Appendices A-D; data for 1999 are extrapolated from currently available data and recent trends.

Our approach to extrapolating growth accounting results through 1999 was to estimate 1999 shares and growth rates for major categories like labour, capital, and information technology components, as well as the output growth. The 1999 labour share was estimated from 1995-98 data, growth in hours worked is from the BLS (2000), and labour quality growth comes from the projections described above. The 1999 growth rates of information technology output were taken from the NIPA, and shares were estimated from 1995-98 data. The 1999 growth rates of information technology inputs were estimated from recent investment data and the perpetual inventory method, and shares were estimated from 1995-98 data. The 1999 growth of other capital was estimates from NIPA investment data for broad categories like equipment and software, non-residential structures, residential structures, as well as consumers' durable purchases; the income share was calculated from the estimated labour share. Output growth was estimated from growth in the BLS business output and the BEA GDP, with adjustment made for different output concepts. Finally, TFP growth for 1999 was estimated as the difference in the estimated output growth and share-weighted input growth.