Projecting Productivity Growth: Lessons from the U.S. Growth Resurgence

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The unusual combination of more rapid output growth and lower inflation from 1995 to 2000 has touched off a strenuous debate among economists about whether improvements in U.S. economic performance can be sustained. This debate has intensified with the recession that began in March 2001, and the economic impacts of the events of September 11 are still imperfectly understood. Both factors add to the considerable uncertainties about future growth that currently face decision makers in both the public and private sectors.

The range of informed opinion can be illustrated by the projections of labor productivity growth reported at the August 2001 Symposium on Economic Policy for the Information Economy, organized by the Federal Reserve Bank of Kansas City. J. Bradford Delong, professor of economics at the University of California at Berkeley, and Lawrence H. Summers, president of Harvard University and former Secretary of the Treasury, offered the most optimistic perspective with a projection of labor productivity growth of 3 percent per year.[1] A more pessimistic tone was set by Martin N. Baily (2001), former chairman of the Council of Economic Advisers, who speculated that labor productivity would average near the low end of the 2 to 2.5 percent per year range.

This uncertainty is only magnified by the observation that recent productivity estimates remain surprisingly strong for an economy in recession. The Bureau of Labor Statistics (BLS) (2002) estimates that business sector productivity grew 1.9 percent per year during 2001 while business sector output grew only 0.9 percent per year as the U.S. economy slowed during the 2001 recession. Growth of both labor productivity and output, however, appears considerably below trend rates, partially reflecting the collapse of investment spending that began toward the end of 2000, continued through 2001, and seems likely to be maintained well into 2002.

This paper reviews the most recent evidence and quantifies the proximate sources of growth using an augmented growth accounting framework that allows us to focus on information technology (IT). Despite the downward revision to gross domestic product (GDP) and investment in some IT assets in the annual GDP revisions by the Bureau of Economic Analysis (BEA) in July 2001, we conclude that the U.S. productivity revival remains largely intact and that IT has played a central role. For example, the capital deepening contribution from computer hardware, software, and telecommunications equipment to labor productivity growth for the 1995–2000 period exceeded the contribution from all other capital assets. We also find increases in total factor productivity (TFP) in both the IT-producing sectors and elsewhere in the economy although the non-IT component is smaller than in earlier estimates.

The paper then turns to the future of U.S. productivity growth, concluding that the projections of Jorgenson and Stiroh (2000), prepared more than eighteen months ago, are largely on target. Our new base-case projection of trend labor productivity growth for the next decade is 2.21 percent per year, only slightly below the average of the 1995–2000 period of 2.36 percent per year. The projection of output growth for the next decade, however, is only 3.31 percent per year, compared with the 1995–2000 average of 4.6 percent, as a result of slower projected growth in hours worked.

Projecting growth for periods as long as a decade is fraught with uncertainty. Our pessimistic projection of labor productivity growth is only 1.33 percent per year, while our optimistic projection is 2.92 percent. For output growth, the range is from 2.43 percent in the pessimistic case to 4.02 percent in the optimistic. These ranges result from fundamental uncertainties about future technological changes in the production of information technology equipment and related investment patterns, which Jorgenson (2001) traced to changes in the product cycle of semiconductors, the most important IT component.

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The starting point for projecting U.S. output growth is the projection of future growth of the labor force. The 2.24 percent per year growth of hours worked from 1995 to 2000 is not likely to be sustainable because labor force growth for the next decade will average only 1.1 percent. An abrupt slowdown in growth of hours worked would have reduced output growth by 1.14 percent, even if labor productivity growth had continued unabated. We estimate that labor productivity growth from 1995 to 2000 also exceeded its sustainable rate, however, leading to an additional decline of 0.15 percent in the trend rate of output growth so that the base-case scenario projects output growth of 3.31 percent for the next decade.

The next section reviews the historical record, extending the estimates of Jorgenson and Stiroh (2000) to incorporate data for 1999 and 2000 and revised estimates of economic growth for earlier years. We employ the same methodology and summarize it briefly. Then we present projections of the trend growth of output and labor productivity for the next decade and compare these with projections based on alternative methodologies.

Reviewing the Historical Record

The methodology for analyzing growth sources is based on the production possibility frontier introduced by Jorgenson (1996, 27–28). This framework captures substitution between investment and consumption goods on the output side and between capital and labor inputs on the input side. Jorgenson and Stiroh (2000) and Jorgenson (2001) have recently used the production possibility frontier to measure the contributions of information technology to U.S. economic growth and the growth of labor productivity.

The production possibility frontier. In the production possibility frontier, output (Y) consist of consumption goods (C) and investment goods (I) while inputs consist of capital services (K) and labor input (L). Output can be further decomposed into IT investment goods—computer hardware (I_c), computer software (I_s), communications equipment (I_m), and all other non-IT output (Y_n). Capital services can be similarly decomposed into the capital service flows from hardware (K_c), software (K_s), communications equipment (K_m), and all other capital services (K_n).[2] The input function (X) is augmented by total factor productivity (A). The production possibility frontier can be represented as

(1) $$Y(Y_n, I_c, I_s, I_m) = A \times X(K_n, K_c, K_s, K_m, L).$$

Under the standard assumptions of competitive product and factor markets and constant returns to scale, equation 1 can be transformed into an equation that accounts for the sources of economic growth:

(2) $$\bar{w}_{Y_n}\Delta \ln Y_n + \bar{w}_{I_c}\Delta \ln I_c + \bar{w}_{I_s}\Delta \ln I_s + \bar{w}_{I_m}\Delta \ln I_m = \bar{v}_{K_n}\Delta \ln K_n + \bar{v}_{K_c}\Delta \ln K_c + \bar{v}_{K_s}\Delta \ln K_s + \bar{v}_{K_m}\Delta \ln K_m + \bar{v}_{L}\Delta \ln L + \Delta \ln A,$$

where $\Delta x = x_t - x_{t-1}$, $\bar{w}$ denotes the average output shares, $\bar{v}$ denotes the average input shares of the subscripted variables, and $\bar{w}_{Y_n} + \bar{w}_{I_c} + \bar{w}_{I_s} + \bar{w}_{I_m} = \bar{v}_{K_n} + \bar{v}_{K_c} + \bar{v}_{K_s} + \bar{v}_{K_m} + \bar{v}_L = 1$. The shares are averaged over periods t and $t-1$. We refer to the share-weighted growth rates in equation 2 as the contributions of the inputs and outputs.

Average labor productivity (ALP) is defined as the ratio of output to hours worked, so that $ALP =$

$y = Y/H$, where the lower-case variable (y) denotes output (Y) per hour (H). Equation 2 can be rewritten in per hour terms as

$$(3)\quad \Delta \ln y = \bar{v}_{K_n} \Delta \ln k_n + \bar{v}_{K_{IT}} \Delta \ln k_{IT} + \bar{v}_L (\Delta \ln L - \Delta \ln H) + \Delta \ln A,$$

where $\bar{v}_{K_{IT}} = \bar{v}_{K_c} + \bar{v}_{K_s} + \bar{v}_{K_m}$ and $\Delta \ln k_{IT}$ is the growth of all IT capital services per hour.

Equation 3 decomposes ALP growth into three sources. The first is capital deepening, defined as the contribution of capital services per hour, which is decomposed into non-IT and IT components. The interpretation of capital deepening is that additional capital makes workers more productive in proportion to the capital share. The second factor is labor quality improvement, defined as the contribution of labor input per hour worked. This factor reflects changes in the composition of the workforce and raises labor productivity in proportion to the labor share. The third source is total factor productivity growth, which raises ALP growth point for point.

In a fully developed sectoral production model, like that of Jorgenson, Ho, and Stiroh (2002), TFP growth reflects the productivity contributions of individual sectors. It is difficult, however, to create the detailed industry data needed to measure industry-level productivity in a timely and accurate manner. The Council of Economic Advisers (CEA) (2001), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000, 2002) have employed the price dual of industry-level productivity to generate estimates of TFP growth in the production of IT assets.

Intuitively, the idea underlying the dual approach is that declines in relative prices for IT investment goods reflect fundamental technological change and productivity growth in the IT-producing industries. We weight these relative price declines by the shares in output of each of the IT investment goods in order to estimate the contribution of IT production to economywide TFP growth. This process enables us to decompose aggregate TFP growth as

$$(4)\quad \Delta \ln A = \bar{u}_{IT} \Delta \ln A_{IT} + \Delta \ln A_n,$$

where $\bar{u}_{IT}$ represents IT's average share of output, $\Delta \ln A_{IT}$ is IT-related productivity growth, and $\bar{u}_{IT} \Delta \ln A_{IT}$ is the contribution to aggregate TFP from IT production. $\Delta \ln A_n$ reflects the contribution to aggregate TFP growth from the rest of the economy, which includes TFP gains in other industries as well as reallocation effects as inputs and outputs are shifted among sectors.

We estimate the contribution to aggregate TFP growth from IT production, $\bar{u}_{IT} \Delta A_{IT}$, by estimating output shares and productivity growth rates for computer hardware, software, and communications equipment. Productivity growth for each investment good is measured as the negative of the rate of price decline relative to the price change of capital and labor inputs. The output shares are the final expenditures on these investment goods, divided by total output.[3] This estimate likely understates IT output because it ignores the production of intermediate goods, but this omission is relatively small. Finally, the non-IT contribution to aggregate TFP growth, ΔA_n, is estimated as a residual from equation 4.

Data. This section briefly summarizes the data required to implement equations 1–4; more detailed descriptions are available in Ho and Jorgenson (1999) and the appendices of Jorgenson and Stiroh (2000). The output measure is somewhat broader than the one used in the official labor productivity statistics, published by the BLS (2001a, 2001b) and employed by Gordon (2000) and Oliner and Sichel (2000, 2002). Our definition of the private U.S. economy includes the nonprofit sector and imputed capital service flows from residential housing and consumer durables. The imputations raise the measure of private output by $778 billion in current dollars, or 9 percent of nominal private GDP, in 2000.

The output estimates reflect the revisions to the U.S. National Income and Product Accounts (NIPA)

1. DeLong and Summers (2001, 21) do not actually provide a point estimate but state that “it is certainly possible—if not probable—that when U.S. growth resumes, trend productivity will grow as fast or faster than it did in the late 1990s.” The 3 percent estimate is attributed to Summers in a review of the symposium in *The Economist*, September 8, 2001.
2. Note that the output and capital service flow concepts include the service flows from residential structures and consumer durables. See Jorgenson and Stiroh (2000) for details.
3. Output shares include expenditures on consumption, investment, government, and net exports for each IT asset. Note that the use of the price dual to measure technological change assumes competitive markets in IT production. As pointed out by Aizcorbe (2002) and Hobijn (2001), the market for many IT components, notably semiconductors and software, is not perfectly competitive, and part of the drop in prices may reflect oligopolistic behavior rather than technological progress. Aizcorbe, however, concludes that declining markups account for only about one-tenth of the measured declines in the price of microprocessors in the 1990s, so the use of prices to measure technological progress seems a reasonable approximation.

released in July 2001. These revisions included a downward adjustment to software investment as well as a new quality-adjusted price index for local area networks. Both of these revisions are incorporated into the estimates of IT investment.

The capital service estimates are based on the Tangible Wealth Survey, published by the BEA and described in Herman (2001). This survey includes data on business investment and consumer durable purchases for the U.S. economy through 2000. We construct capital stocks from the investment data by the perpetual inventory method and assume that the effective capital stock for each asset is the average of the current and lagged estimates. The data on tangible assets from the BEA are augmented with inventory data to form the measure of the reproducible capital stock. The total capital stock also includes land and inventories.

Changes in the underlying trend growth rate of productivity are likely to be permanent, but cyclical factors such as strong output growth or extraordinarily rapid investment are more likely to be temporary.

Finally, we estimate capital service flows by multiplying rental prices and effective capital stocks, as originally proposed by Jorgenson and Griliches (1996). The estimates incorporate asset-specific differences in taxes, asset prices, service lives, and depreciation rates. This method is essential for understanding the productive impact of IT investment because IT assets differ dramatically from other assets in rates of decline of asset prices and depreciation rates.

The difference between the growth in aggregate capital service flows and effective capital stocks is referred to as the growth in capital quality. That is,

(5) $\Delta \ln KQ = \Delta \ln K - \Delta \ln Z$,

where KQ is capital quality, K is capital service flow, and Z is the effective capital stock. The aggregate capital stock, Z, is a quantity index over seventy different effective capital stocks plus land and inventories using investment goods prices as weights. The aggregate flow of capital services, K, is a quantity index of the same stocks using rental (or service) prices as weights. The difference in growth rates is the growth rate of capital quality, KQ. As firms substitute among assets by investing relatively more in assets with relatively high marginal products, capital quality increases.

Labor input is a quantity index of hours worked that takes into account the heterogeneity of the work force among sex, employment class, age, and education levels. The weights used to construct the index are the compensation of the various types of workers. In the same way as for capital, we define growth in labor quality as the difference between the growth rate of aggregate labor input and hours worked:

(6) $\Delta \ln LQ = \Delta \ln L - \Delta \ln H$,

where LQ is labor quality, L is the labor input index, and H is hours worked. As firms substitute among hours worked by hiring relatively more highly skilled and highly compensated workers, labor quality rises.

The labor data incorporate the Censuses of Population for 1970, 1980, and 1990, the annual Current Population Surveys (CPS), and the NIPA. This study takes total hours worked for private domestic employees directly from the NIPA (Table 6.9c), self-employed hours worked for the nonfarm business sector from the BLS, and self-employed hours worked in the farm sector from the Department of Agriculture.

Results. Table 1 reports the estimates of the components of equation 2, the sources of economic growth. For the period as a whole, output grew approximately 3.6 percent per year. Capital input made the largest contribution to growth of 1.8 percentage points, followed by approximately 1.2 percentage points from labor input. Less than 20 percent of output growth, 0.7 percentage point, directly reflects TFP. These results are consistent with the other recent growth accounting decompositions like CEA (2001), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000, 2002).

The data also show the substantial acceleration in output growth after 1995. Output growth increased from 3 percent per year for the 1973–95 period to 4.6 percent for the 1995–2000 period, reflecting large increases in IT and non-IT investment goods. On the input side, more rapid capital accumulation contributed 0.84 percentage point to the post-1995 acceleration while faster growth of labor input contributed 0.30 percentage point and accelerated TFP growth the remaining 0.47 percentage point. The contribution of capital input from IT increased from 0.36 percentage point per year for the 1973–95 period to 0.85 for the 1995–2000 period, exceeding the increased contributions of all other forms of capital.

TABLE 1

Sources of Growth in Private Domestic Output, 1959–2000

	1959–2000	1959–73	1973–95	1995–2000	1995–2000 less 1973–95
Growth in private domestic output (Y)	3.61	4.24	2.99	4.60	1.61
Contribution of selected output components					
Other output (Y_n)	3.30	4.10	2.68	3.79	1.12
Computer investment (I_c)	0.16	0.07	0.17	0.37	0.20
Software investment (I_s)	0.09	0.03	0.09	0.26	0.18
Communications investment (I_m)	0.07	0.05	0.06	0.17	0.11
Contribution of capital and CD services (K)	1.80	1.99	1.54	2.38	0.84
Other (K_n)	1.44	1.81	1.18	1.52	0.34
Computers (K_c)	0.19	0.09	0.20	0.47	0.28
Software (K_s)	0.09	0.03	0.09	0.25	0.16
Communications (K_m)	0.08	0.06	0.07	0.13	0.06
Contribution of labor (L)	1.16	1.12	1.12	1.42	0.30
Aggregate total factor productivity (TFP)	0.66	1.13	0.33	0.80	0.47
Contribution of capital and CD quality	0.47	0.34	0.41	1.09	0.69
Contribution of capital and CD stock	1.33	1.65	1.14	1.28	0.15
Contribution of labor quality	0.28	0.39	0.23	0.17	–0.06
Contribution of labor hours	0.88	0.73	0.89	1.26	0.37

Note: A contribution of an output or input is defined as the share-weighted, real growth rate. "CD" stands for consumer durables.
Source: Authors' calculations based on BEA, BLS, Census Bureau, and other data

The last four rows in Table 1 present an alternative decomposition of the contribution of capital and labor inputs using equations 5 and 6. Here, the contribution of capital and labor reflects the contributions from capital quality and capital stock as well as labor quality and hours worked, respectively, as

$$(7)\quad \Delta \ln Y = \bar{v}_K \Delta \ln Z + \bar{v}_K \Delta \ln KQ + \bar{v}_L \Delta \ln H + \bar{v}_L \Delta \ln LQ + \Delta \ln A.$$

Table 1 shows that the revival of output growth after 1995 can be attributed to two forces. First, a massive substitution toward IT assets in response to accelerating IT price declines is reflected in the rising contribution of capital quality while the growth of capital stock lagged considerably behind the growth of output. Second, the growth of hours worked surged as the growth of labor quality declined. A fall in the unemployment rate and an increase in labor force participation drew more workers with relatively low marginal products into the workforce. We employ equation 7 in projecting sustainable growth of output and labor productivity in the next section.

Table 2 presents estimates of the sources of ALP growth, as in equations 3 and 4. For the period as a whole, growth in ALP accounted for nearly 60 percent of output growth, due to annual capital deepening of 1.13 percentage points, improvement of labor quality of 0.28 percentage point, and TFP growth of 0.66 percentage point. Growth in hours worked of 1.54 percentage points per year accounted for the remaining 40 percent of output growth.

Looking more closely at the post-1995 period, one sees that labor productivity increased by 0.92 percentage points per year from 1.44 for the 1973–95 period to 2.36 for the 1995–2000 period, and hours worked increased by 0.68 percentage points from an annual rate of 1.55 for the 1973–95 period to 2.24 for the 1995–2000 period. The labor productivity growth revival reflects more rapid capital deepening of 0.52 percentage point and accelerated TFP growth of 0.47 percentage point per year; the contribution of labor quality declined. Nearly all of the increase in capital deepening was from IT assets with only a small increase from other assets. Finally, we estimate that improved productivity in the production of IT-related assets contributed 0.27 percentage

TABLE 2

Sources of Growth in Average Labor Productivity, 1959–2000

	1959–2000	1959–73	1973–95	1995–2000	1995–2000 less 1973–95
Output growth (*Y*)	3.61	4.24	2.99	4.60	1.61
Hours growth (*H*)	1.54	1.27	1.55	2.24	0.68
Average labor productivity growth (ALP)	2.07	2.97	1.44	2.36	0.92
Capital deepening	1.13	1.44	0.88	1.40	0.52
IT capital deepening	0.32	0.16	0.32	0.76	0.44
Other capital deepening	0.82	1.28	0.56	0.64	0.08
Labor quality	0.28	0.39	0.23	0.17	–0.06
TFP growth	0.66	1.13	0.33	0.80	0.47
IT-related contribution	0.23	0.10	0.24	0.51	0.27
Other contribution	0.43	1.03	0.08	0.29	0.20

Note: A contribution of an output or input is defined as the share-weighted, real growth rate.
Source: Authors' calculations based on BEA, BLS, Census Bureau, and other data

point to aggregate TFP growth while improved productivity growth in the rest of the economy contributed the remaining 0.2 percentage point. These results suggest that IT had a substantial role in the revival of labor productivity growth through both capital deepening and TFP channels.

Our estimate of the magnitude of the productivity revival is somewhat lower than that reported in earlier studies by BLS (2001a), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000). These studies were based on data reported prior to the July 2001 revision of the NIPA, which substantially lowered GDP growth in 1999 and 2000. Our estimates of the productivity revival are also lower than the estimates in BLS (2001b), however, which does include the July 2001 revisions in GDP.

BLS (2001b) reports business sector ALP growth of 2.68 percentage points for 1995–2000 and 1.45 for 1973–95, an increase of 1.23 percentage points, compared to our estimated acceleration of 0.92 percentage point. This divergence results from a combination of a slower acceleration of our broader concept of output and our estimates of more rapid growth in hours worked. BLS (2001b), for example, reports that hours grew 1.95 percent per year for the 1995–2000 period in the business sector while our estimate is 2.24.

Our estimate of private domestic employee hours is taken directly from the NIPA and includes workers in the nonprofit sector, and the BLS estimate does not. In addition, BLS (2001b) has revised the growth in business sector hours in 2000 downward by 0.4 percentage point on the basis of new data from the *2000 Hours at Work Survey*. Our estimate of labor quality change is also slightly different from BLS (2001a) because of the different methods of estimating the wage-demographic relationships and our use of only the March CPS data as opposed to the monthly CPS data used by BLS. These differences ultimately appear in our estimated contribution to TFP from non-IT sources because this cannot be observed directly without detailed industry data, and we therefore estimate it as a residual.

Projecting Productivity Growth

While there is little disagreement about the resurgence of ALP growth after 1995, there has been considerable debate about whether this is permanent or temporary. Changes in the underlying trend growth rate of productivity are likely to be permanent, but cyclical factors such as strong output growth or extraordinarily rapid investment are more likely to be temporary. This distinction is crucial to understanding the sources of the recent productivity revival and projecting future productivity growth.

This section presents projections of trend rates of growth for output and labor productivity over the next decade, abstracting from business cycle fluctuations. The key assumptions are that output and the reproducible capital stock will grow at the same rate and that labor hours will grow at the same rate as the labor force.[4] These features are characteristic of the U.S. and most industrialized economies over periods of time longer than a typical business cycle. For example, U.S. output growth averaged 3.6 percent per year for the 1959–2000 period while our measure of the reproducible capital stock grew 3.9 percent per year.[5]

We begin by decomposing the aggregate capital stock into the reproducible component, Z_R, and business sector land, *LAND*, which we assume to be fixed. This decomposition implies that

$$(8)\quad \Delta\ln Z = \bar{\mu}_R \Delta\ln Z_R + (1 - \bar{\mu}_R)\Delta\ln LAND = \bar{\mu}_R \Delta\ln Z_R,$$

where $\bar{u}_R$ is the value share of reproducible capital stock in total capital stock.

We then employ our projection assumptions to construct estimates of trend output and productivity growth, which are conditional on the projected growth of the remaining sources of economic growth. More formally, if $\Delta\ln Y = \Delta\ln Z_R$, then combining equations 3, 4, 7, and 8 implies that trend labor productivity and output growth are given by

$$(9)\quad \Delta\ln y = [\bar{v}_K \Delta\ln KQ - \bar{v}_K(1-\bar{\mu}_R)\Delta\ln H + \bar{v}_L \Delta\ln LQ + \bar{u}_{IT}\Delta\ln A_{IT} + \ln A_n]/(1-\bar{v}_K\bar{\mu}_R)$$
$$\Delta\ln Y = \Delta\ln y + \Delta\ln H.$$

Equation 9 is a long-run relationship that averages over cyclical and stochastic elements and removes the transitional dynamics relating to capital accumulation. The second part of a definition of trend growth is that the unemployment rate remains constant and hours growth matches labor force growth. Growth in hours worked was exceptionally rapid in the 1995–2000 period as the unemployment rate fell from 5.6 percent in 1995 to 4 in 2000, so output growth was considerably above its trend rate.[6] To estimate hours growth over the next decade, we employ detailed demographic projections based on Census Bureau data.

To complete intermediate-term growth projections based on equation 9 requires estimates of capital and labor shares, IT output shares, reproducible capital stock shares, capital quality growth, labor quality growth, and TFP growth. Labor quality growth and the various shares are relatively easy to project, but extrapolations of the other variables involve much greater uncertainty. Accordingly, we present three sets of projections—a base-case scenario, a pessimistic scenario, and an optimistic scenario.

We hold labor quality growth, hours growth, the capital share, the reproducible capital stock share, and the IT output share constant across the three scenarios and refer to these as the "common assumptions." We vary IT-related TFP growth, the contribution to TFP growth from non-IT sources, and capital quality growth across these scenarios and label them "alternative assumptions." Generally speaking for these variables, the base-case scenario incorporates data from the 1990–2000 business cycle, the optimistic scenario assumes the patterns of the 1995–2000 period will persist, and the pessimistic case assumes that the economy reverts to 1973–95 averages.

Common assumptions. Hours growth ($\Delta\ln H$) and labor quality growth ($\Delta\ln LQ$) are relatively easy to project. The Congressional Budget Office (CBO) (2001a), for example, projects growth in the economywide labor force of 1.1 percent per year based on Social Security Administration projections of population growth. Potential hours growth is projected at 1.2 percent per year for the nonfarm business sector for 2001–11 based on CBO projections of hours worked for different demographic categories of workers. The CBO estimate of potential hours growth is a slight increase from earlier projections due to incorporation of recent data from the 2000 census and changes in the tax laws that will modestly increase the supply of labor. The CBO (2001a) does not employ the concept of labor quality.

An important difficulty in projecting capital quality growth from recent data is that investment patterns in the 1990s may partially reflect an unsustainable investment boom in response to temporary factors like Y2K investment and the Nasdaq stock market bubble.

We construct our own projections of demographic trends. Ho and Jorgenson (1999) have shown that the dominant trends in labor quality growth are due to rapid improvements in educational attainment in the 1960s and 1970s and the rise in female participation rates in the 1970s. Although the average educational level continued to rise as younger and

4. The assumption that output and the capital stock grow at the same rate is similar to a balanced growth path in a standard growth model, but our actual data with many heterogeneous types of capital and labor inputs make this interpretation only an approximation.
5. Reproducible assets include equipment, structures, consumer durable assets, and inventories but exclude land.
6. These unemployment rates are annual averages for the civilian labor force sixteen years and older from the BLS.

better-educated workers entered the labor force and older workers retired, the improvement in educational attainment of new entrants into the labor force largely ceased in the 1990s.

Growth in the population is projected from the Bureau of the Census demographic model, which breaks the population down by individual year of age, race, and sex.[7] For each group, the population in period t is equal to the population in period $t - 1$, less deaths plus net immigration. Death rates are group-specific and are projected by assuming a steady rate of improvement in health. The population of newborns in each period reflects the number of females in each age group and the age- and race-specific fertility rates. These fertility rates are projected to fall steadily.

Our optimistic scenario puts labor productivity growth just below 3 percent per year and reflects the assumption of continuing rapid technological progress.

We observe labor force participation rates in the last year of our sample period and then project the work force by assuming constant participation rates for each sex-age group. The educational attainment of workers aged α in period t is projected by assuming that it is equal to the attainment of the workers of age $\alpha - 1$ in period $t - 1$ for all those who are over thirty-five years old in the last year of the sample. For those who are younger than thirty-five, we assume that the educational attainment of workers aged α in forecast period t is equal to the attainment of workers aged α in the base year.

The index of labor quality is constructed from hours worked and compensation rates. We project hours worked by multiplying the projected population in each sex-age-education group by the annual hours worked per person in the last year of the sample. The relative compensation rates for each group are assumed to be equal to the observed compensation in the sample period. With these projected hours and compensation we forecast the quality index over the next twenty years.

Our estimates suggest that hours growth ($\Delta \ln H$) will be about 1.1 percent per year over the next ten years, which is quite close to the CBO (2001a) estimates, and 0.8 percent per year over a twenty-year period. We estimate that growth in labor quality ($\Delta \ln LQ$) will be 0.27 percent per year over the next decade and 0.17 percent per year over the next two decades. This estimate is considerably lower than the 0.49 percent growth rate for the 1959–2000 period, which was driven by rising average educational attainment and stabilizing female participation.

The capital share ($\bar{v}_K$) has not shown any obvious trend over the last forty years. We assume it holds constant at 42.8 percent, the average for 1959–2000. Similarly, the fixed reproducible capital share ($\bar{\mu}_R$) has shown little trend, and we assume it remains constant at 80.4 percent, the average for 1959–2000.

We assume the IT output share ($\bar{u}_{IT}$) stays at 5.1 percent, the average for the 1995–2000 period. This estimate is likely conservative because IT has steadily increased in importance in the U.S. economy, rising from 2.1 percent of output in 1970 to 2.7 percent in 1980, 3.9 percent in 1990, and 5.7 percent in 2000. On the other hand, there has been speculation that IT expenditures in the late 1990s were not sustainable because of Y2K investment, the Nasdaq bubble, and abnormally rapid price declines.[8]

Alternative assumptions. IT-related productivity growth ($\Delta \ln A_{IT}$) has been extremely rapid in recent years with a substantial acceleration after 1995. For the 1990–95 period productivity growth for production of the three IT assets averaged 7.4 percent per year while the 1995–2000 average growth rate was 10.3 percent. These growth rates are high but quite consistent with industry-level productivity estimates for high-tech sectors. For example, BLS (2001a) reports productivity growth of 6.9 percent per year for the 1995–99 period in industrial and commercial machinery, which includes production of computer hardware, and 8.1 percent in electronic and other electric equipment, which includes semiconductors and telecommunications equipment.

Jorgenson (2001) argues that the large increase in IT productivity growth was triggered by a much sharper acceleration in the decline of semiconductor prices that can be traced to a shift in the product cycle for semiconductors in 1995 from three years to two years, a consequence of intensifying competition in the semiconductor market. It would be premature to extrapolate the recent acceleration in productivity growth into the indefinite future, however, because this depends on the persistence of a two-year product cycle for semiconductors.

To better gauge the future prospects of technological progress in the semiconductor industry, we turn to the *International Technology Roadmap* *for Semiconductors* (2000). This projection, performed annually by a consortium of industry associations, forecasts a two-year product cycle through 2003 and a three-year product cycle thereafter. The *Roadmap* is a reasonable basis for projecting the IT-related productivity growth of the U.S. economy. Moreover, continuation of a two-year cycle provides an upper bound for growth projections while reversion to a three-year cycle gives a lower bound.

Our base-case scenario follows the *Roadmap* and averages the two-year and three-year cycle projections with IT-related growth of 8.8 percent per year, which equals the average for the 1990–2000 period. The optimistic projections assume that the two-year product cycle for semiconductors remains in place over the intermediate future so that productivity growth in the production of IT assets averages 10.3 percent per year, as it did for 1995–2000. The pessimistic projection assumes the semiconductor product cycle reverts to the three-year cycle in place during the 1973–95 period when IT-related productivity growth was 7.4 percent per year. In all cases, the contribution of IT to aggregate TFP growth reflects the 1995–2000 average share of about 5.1 percent.

The TFP contribution from non-IT sources (ΔA_n) is more difficult to project because the post-1995 acceleration is outside of standard growth models. Therefore, we present a range of alternative estimates that are consistent with the historical record. The base case uses the average contribution from the full business cycle of the 1990s and assumes a contribution of 0.2 percentage point for the intermediate future. This base case assumes that the myriad of factors that drove TFP growth in the 1990s—such as technological progress, innovation, resource reallocations, and increased competitive pressures—will continue into the future. The optimistic case assumes that the contribution for 1995–2000 of 0.29 percentage point per year will continue for the intermediate future while our pessimistic case assumes that the U.S. economy will revert to the slow-growth 1973–95 period, when this contribution averaged only 0.08 percent per year.

The final step in our projections is to estimate the growth in capital quality ($\Delta \ln KQ$). The workhorse aggregate growth model with one capital good has capital stock and output growing at the same rate in a balanced growth equilibrium, and even complex models typically have only two capital goods. The U.S. data, however, distinguish between several dozen types of capital, and the historical record shows that substitution between these types of capital is an important source of output and productivity growth. For 1959–2000, for example, capital quality growth contributed 0.47 percentage point to output growth as firms substituted toward short-lived assets with higher marginal products. This contribution corresponds to a growth in capital quality of about 1 percent per year.

An important difficulty in projecting capital quality growth from recent data, however, is that investment patterns in the 1990s may partially reflect an unsustainable investment boom in response to temporary factors like Y2K investment and the Nasdaq stock market bubble, which skewed investment toward IT assets. Capital quality for the 1995–2000 period grew at 2.5 percent per year as firms invested heavily in IT, for example, but there has been a sizable slowdown in IT investment in the second half of 2000 and in 2001. Therefore, we are cautious about relying too heavily on the recent investment experience.

Our primary conclusion is that a consensus has emerged about trend rates of growth for output and labor productivity.

The base case again uses the average rate for 1990–2000, which was 1.75 percentage points for capital quality; this rate effectively averages the high substitution rates in the late 1990s with the more moderate rates of the early 1990s and uses evidence from the complete business cycle of the 1990s. The optimistic projection ignores the belief that capital substitution was unsustainably high in the late 1990s and assumes that capital quality growth will continue at the 2.45 percent annual rate of the 1995–2000 period. Our pessimistic scenario assumes that the growth of capital quality reverts to the 0.84 percent annual growth rate seen for the 1973–95 period.

Output and productivity projections. Table 3 assembles the components of the projections and presents the three scenarios. The top section shows the projected growth of output, labor productivity, and the effective capital stock. The middle section

7. See Bureau of the Census (2000) for details of the population model.

8. See McCarthy (2001) for determinants of investment in the late 1990s.

TABLE 3

Output and Labor Productivity Projections

	1995–2000	Scenarios: Pessimistic	Base-Case	Optimistic
			Projections	
Output growth	4.60	2.43	3.31	4.02
ALP growth	2.36	1.33	2.21	2.92
Effective capital stock	2.94	1.96	2.66	3.23
			Common assumptions	
Hours growth	2.240	1.100	1.100	1.100
Labor quality growth	0.299	0.265	0.265	0.265
Capital share	0.438	0.428	0.428	0.428
IT output share	0.051	0.051	0.051	0.051
Reproducible capital stock share	0.798	0.804	0.804	0.804
			Alternative assumptions	
TFP growth in IT	10.33	7.39	8.78	10.28
Implied IT-related TFP contribution	0.52	0.37	0.44	0.52
Other TFP contribution	0.29	0.08	0.20	0.29
Capital quality growth	2.45	0.84	1.75	2.45

Notes: In all projections, hours growth and labor quality growth are from internal projections, capital share and reproducible capital stock shares are 1959–2000 averages, and IT output shares are for 1995–2000. The pessimistic case uses 1973–95 average growth of capital quality, IT-related TFP growth, and non-IT TFP contribution. The base case uses 1990–2000 averages, and the optimistic case uses 1995–2000 averages.

reports the five factors that are held constant across scenarios—hours growth, labor quality growth, the capital share, the IT output share, and the reproducible capital stock share. The bottom section includes the three components that vary across scenarios—TFP growth in IT, the TFP contribution from other sources, and capital quality growth. Table 3 also compares the projections with actual data for the same series for 1995–2000.

The base-case scenario puts trend labor productivity growth at 2.21 percent per year and trend output growth at 3.31 percent per year. Projected productivity growth falls just short of our estimates for the 1995–2000 period, but output growth is considerably slower due to the large slowdown in projected hours growth; hours grew 2.24 percent per year for the 1995–2000 period compared to our projection of only 1.1 percent per year for the next decade. Capital stock growth is projected to fall in the base case to 2.66 percent per year from 2.94 percent for the 1995–2000 period.

Our base-case scenario incorporates the underlying pace of technological progress in semiconductors embedded in the *Roadmap* forecast and puts the contribution of IT-related TFP below that of the 1995–2000 period as the semiconductor industry eventually returns to a three-year product cycle. The slower growth is partially balanced by larger IT output shares. Other TFP growth also makes a smaller contribution. Finally, the slower pace of capital input growth is offset by slower hours growth so that strong capital deepening brings the projected growth rate near the observed rates of growth for 1995–2000.

Our optimistic scenario puts labor productivity growth just below 3 percent per year and reflects the assumption of continuing rapid technological progress. In particular, the two-year product cycle in semiconductors is assumed to persist for the intermediate future, driving rapid TFP in production of IT assets as well as continued substitution toward IT assets and rapid growth in capital quality. In addition, other TFP growth continues the relatively rapid contribution seen after 1995.

Finally, the pessimistic projection of 1.33 percent annual growth in labor productivity assumes that many trends revert to the sluggish growth rates of the 1973–95 period and that the three-year product cycle for semiconductors begins immediately. The larger share of IT, however, means that even with the return to the three-year technology cycle and slower TFP growth, labor productivity growth will equal the rates seen in the 1970s and 1980s.

Alternative Methodologies and Estimates

This section briefly reviews alternative approaches to estimating productivity growth trends from the historical record and projecting productivity growth going forward. We begin with the econometric methods for separating trend and cyclical components of productivity growth employed by Gordon (2000), French (2001), and Roberts (2001). A second approach is to control for factors that are most likely to be cyclical, such as factor utilization, in the augmented growth accounting framework of Basu, Fernald, and Shapiro (2001). In a third approach, the CBO (2001a, 2001b) calibrates a growth model to the historical record and uses the model to project growth of output and productivity. Finally, Oliner and Sichel (2002) present a projection methodology based on a growth accounting framework; this paper appears in this issue of the *Economic Review* and is not discussed in detail here.

Econometric estimates. We begin with the studies that employ econometric methods for decomposing a single time series between cyclical and trend components. Gordon (2000) estimates that of the 2.75 percent annual labor productivity growth rate during the 1995–99 period, 0.5 percent can be attributed to cyclical effects and 2.25 percent to trend. The post-1995 trend growth rate is 0.83 percent higher than the growth rate in the 1972–95 period. Capital and labor input growth and price measurement changes account for 0.52 percent, and TFP growth in the computer sector accounts for 0.29 percent, leaving a mere 0.02 percent to be explained by acceleration in TFP growth in the other sectors of the private economy. In this view the productivity revival is concentrated in the computer-producing sector.

Other studies have employed state-space models to distinguish between trend and cycles for output. Roberts (2001) uses time-varying parameter methods to model the growth of labor and total factor productivity. He represents trend productivity as a random walk with drift and allows the drift term to be a time-varying parameter. These estimates suggest that trend labor productivity growth has increased from 1.6 percent per year during the 1973–94 period to 2.7 percent by 2000 while trend TFP growth rose from 0.5 percent during the 1985–95 period to 1.1 percent during the 1998–2000 period. This estimate of trend labor productivity falls between our base-case and optimistic projections.

French (2001) uses a Cobb-Douglas production function to model trends and cycles in total factor productivity growth. He considers filtering methods and concludes that they are all unsatisfactory because of the assumption that innovations are normally distributed.[9] He applies a discrete innovations model with two high-low TFP growth regimes and finds that the trend TFP growth after 1995 increases from 1.01 percent to 1.11 percent.

Finally, Hansen (2001) provides a good primer on recent advances in the alternatives to random walk models—testing for infrequent structural breaks in parameters. Applying these methods to the U.S. manufacturing sector, he finds strong evidence of a break in labor productivity in the mid-1990s, the break date depending on the sector being analyzed. We do not compare his specific estimates because they are only for manufacturing.

Our second conclusion is that trend growth rates are subject to considerable uncertainty. For the U.S. economy this can be identified with the future product cycle for semiconductors and the impact on other high-tech gear.

Augmented growth accounting. Basu, Fernald, and Shapiro (2001) present an alternative approach to estimating trend growth in total factor productivity by separately accounting for factor utilization and factor accumulation. They extend the growth accounting framework to incorporate adjustment costs, scale economies, imperfect competition, and changes in utilization. Industry-level data for the 1990s suggest that the post-1995 rise in productivity appears to be largely a change in trend rather than a cyclical phenomenon since there was little change in utilization in the late 1990s. While Basu, Fernald, and Shapiro are clear that they do not make predictions about the sustainability of these changes, their results suggest that any slowdown in investment growth is likely to be associated with a temporary increase in output growth as resources are reallocated away from adjustment and toward production.

Calibration and projection. The CBO (2001a) presents medium-term projections for economic growth and productivity for the 2003–11 period for both the overall economy and the nonfarm business sector. The CBO's most fully developed model is for the nonfarm business sector. Medium-term projections are based on historical trends in the labor force, savings and investment, and TFP growth.

9. Both Roberts (2001) and French (2001) employ the Stock and Watson (1998) method of dealing with the zero bias.

These projections allow for possible business cycle fluctuations, but the CBO does not explicitly forecast fluctuations beyond two years (CBO 2001a, 38).

For the nonfarm part of the economy, the CBO (2001a) projects potential output growth of 3.7 percent per year and potential labor productivity of 2.5 percent per year. For the economy as a whole, the CBO projects potential labor productivity growth of 2.1 percent per year, which is quite close to our estimates.

For the nonfarm business economy, the CBO (2001a) utilizes a Cobb-Douglas production function without labor quality improvement. The CBO's relatively high projection of labor productivity growth for the nonfarm business sector reflects projections of capital input growth of 4.8 percent per year and TFP growth of 1.4 percent per year.[10] The CBO's relatively rapid rate of capital input growth going forward is somewhat slower than their estimate of 5.2 percent for the 1996–2000 period but considerably faster than their estimate of 3.9 percent annual growth for the 1990–2000 period. These estimates reflect the model of savings and investment used by the CBO as well as the expectation of continued substitution toward short-lived IT assets. Potential TFP growth of 1.4 percent per year reflects an estimated trend growth of 1.1 percent per year augmented by the specific effects of computer quality improvement and changes in price measurement.

Conclusion

Our primary conclusion is that a consensus has emerged about trend rates of growth for output and labor productivity. Our central estimates of 2.21 percent for labor productivity and 3.31 percent for output are very similar to those of Gordon (2000) and the CBO (2001a) and only slightly more optimistic than Baily's (2001).[11] Our methodology assumes that trend growth rates in output and reproducible capital are the same and that hours growth is constrained by the growth of the labor force to form a balanced growth path. While productivity is projected to fall slightly from the pace seen in late 1990s, we conclude that the U.S. productivity revival is likely to remain intact for the intermediate future.

Our second conclusion is that trend growth rates are subject to considerable uncertainty. For the U.S. economy this can be identified with the future product cycle for semiconductors and the impact on other high-tech gear. The switch from a three-year to a two-year product cycle in 1995 produced a dramatic increase in the rate of decline of IT prices. This is reflected in the investment boom of the 1995–2000 period and the massive substitution of IT capital for other types of capital that took place in response to price changes. The issue that must be confronted by policymakers is whether this two-year product cycle can continue and whether firms will continue to respond to the dramatic improvements in the performance/price ratio of IT investment goods.

As a final point, we have not tried to quantify another important source of uncertainty, namely, the economic impacts of the events of September 11. These impacts are already apparent in the slowdown of economic activity in areas related to travel and increased security as well as higher government expenditures for the war in Afghanistan and enhanced homeland security. The cyclical effects will likely produce only a temporary reduction in productivity as civilian plants operate at lower utilization rates. Even a long-term reallocation of resources from civilian to public goods or to security operations, however, should produce only a one-time reduction in productivity levels rather than a change in the trend rate of growth of output and productivity.

10. See CBO (2001b) for details. Note also that the CBO assumes a capital share of 0.3, which is substantially smaller than our estimate of 0.43.

11. Note that our output concept is slightly different so the estimates are not directly comparable. Nonetheless, the broad predictions are similar.

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