Preface: Technology, Growth, and the Labor Market

DONNA K. GINTHER AND MADELINE ZAVODNY

Ginther is an associate professor of economics at the University of Kansas and a former research economist and associate policy adviser at the Atlanta Fed. Zavodny is an associate professor of economics at Occidental College and is currently on leave from her position as a research economist and associate policy adviser at the Atlanta Fed. *They extend many thanks to presenters and discussants (whose names appear in this preface) as well as conference participants at the January 2002 "Technology, Growth, and the Labor Market" conference. The views expressed in the conference proceeding papers presented in this issue of the Economic Review are the authors' and should not be attributed to any institutions in the Federal Reserve System or any other institutions with which the authors are affiliated.*[1]

In 1998, Federal Reserve Board Chairman Alan Greenspan posed the provocative question, Is there a "new economy"? He described the new economy's characteristics as including technological innovations that raise productivity and that have, accordingly, removed pricing power from the world's producers on a more lasting basis (Greenspan 1998). Although the 2001 recession quelled the discussion about whether the United States, and perhaps even the world, had entered a new era characterized by sustained high levels of economic growth, researchers continue to investigate the effects of technological change on the economy.

This issue of the *Economic Review* contains four papers that examine the underpinnings of the new economy—technology and its effects on macroeconomic growth and the labor market. These papers were among those presented at the "Technology, Growth, and the Labor Market" conference sponsored by the research department of the Federal Reserve Bank of Atlanta and the Andrew Young School of Policy Studies at Georgia State University in January this year. This introduction summarizes all the speeches, papers, and discussant comments presented at the conference.[2]

Researchers were quick to examine the new economy, but many of their early conclusions remain open to debate. Macroeconomists, including Martin N. Baily (2001), Stephen D. Oliner and Daniel E. Sichel (2000), and Kevin Stiroh (2001), argued that the technological change embodied in increased computer investment contributed substantially to the surge in productivity growth experienced in the United States between 1995 and 2000. Although productivity traditionally declines during recessions, labor productivity remained high during the recession that officially began in March 2001, perhaps because the large investments in equipment and software made during the late 1990s continued to boost output for several years after the purchases were made. However, the advent of the 2001 recession and research by skeptics, such as Robert J. Gordon (2000), indicate that the effect of technology on current and future productivity growth remains an open question.

Labor economists have also investigated technology's impact on the wage structure. The generally accepted hypothesis among labor economists is that skill-biased technological change has increased the relative demand for skilled workers, causing the observed increase in earnings inequality in the 1980s (Council of Economic Advisers 1997; Katz and Autor 1999). Articles by, among others, Alan B. Krueger (1993), Eli Berman, John Bound, and Zvi Griliches (1994), and Ann P. Bartel and Nachum Sicherman (1998) noted an association between computerization and higher wages for skilled workers. However, the skill-biased technological change hypothesis has been difficult to prove because of the paucity of data on workers' use of technology in the workplace.

Other research has attempted to forge a link between human resource practices, computerization, productivity, and the returns to skill. Casey Ichniowski and Kathryn Shaw (1995, 1999, and 2000) argued that innovative human resource practices raise worker productivity in a variety of contexts. Peter Cappelli and William Carter (2000) evaluated the relative contributions of computerization and high-performance workplace practices, concluding that higher wages are associated with both technology (as represented by computers) and high-performance workplace practices. This research suggests that, in addition to technology, human resource practices may be contributing to higher productivity growth.

Productivity and the Macroeconomy

The conference included two plenary talks by economists with firsthand experience in determining how productivity, inequality, and other such factors should be taken into account when setting monetary policy. The speeches by Edward M. Gramlich and Alice M. Rivlin framed the questions addressed by conference participants. Gramlich discussed why understanding the role of technology in the economy is important to economists and monetary policymakers. He raised many issues, including what stage of an "information transformation" the U.S. economy is in, why productivity defied past patterns by holding up during the 2001 recession, the relative merits of public versus private investment, and why the United States experienced a much larger productivity spurt during the late 1990s than Western European nations that had access to the same technologies.

Rivlin discussed the relevance of the new economy paradigm and whether the economic recovery in the United States will continue to feature high productivity growth and low inflation and unemployment. She indicated that the Internet, combined with a number of advances in business practices, has led to an increase in economic potential. One of the key implications of being in a new economy is that inflation has become less of a concern for monetary policymakers because employers are able to raise wages without passing higher labor costs along via price increases. Instead, excessive investments and overvalued equity markets are central concerns going forward. Unfortunately, she noted, monetary policymakers have less influence over such factors than over inflation.

Productivity Growth and Technology: What the Future Holds

The conference included two papers, printed in this *Review,* that discussed the sources of the surge in labor productivity growth during the latter half of the 1990s and presented forecasts of labor productivity growth rates during the next few years. The two papers are similar in their methodologies and findings and also dovetail with recent research by Baily (2001).

Dale W. Jorgenson, Mun S. Ho, and Kevin J. Stiroh reviewed recent studies on the sustainable rate of labor productivity growth and quantified the source of growth, focusing on information technology (IT). Using an augmented growth accounting framework, they concluded that the resurgence of labor productivity growth during the late 1990s remains intact despite the 2001 recession. They projected that trend labor productivity growth during the next decade will be about 2.2 percent per year, with a range of 1.3 percent to 2.9 percent, and output growth will be about 3.3 percent per year, with a range of 2.3 percent to 4.0 percent. Jorgenson, Ho, and Stiroh found that IT, particularly semiconductors, played a large role in growth during the second half of the 1990s, a trend that is expected to continue but is nonetheless uncertain.

Stephen D. Oliner and Daniel E. Sichel used a similar growth accounting framework to explore the role of IT in labor productivity growth. They also analyzed the steady-state properties of a multisector growth model in order to estimate the long-run rate of labor productivity growth and to calculate to what extent technical progress drives productivity improvements. Oliner and Sichel concluded that the likely annual rate of labor productivity growth is about 2 to 2.75 percent, depending on the pace of technological advances in the semiconductor industry. This conclusion implies that the rates of labor productivity growth achieved in the United States during the second half of the 1990s are sustainable.

The discussion of these two papers by John Fernald noted that the estimates of labor productivity growth might be on the conservative side because the papers do not account for adjustment costs. The high levels of investment in IT during the second half of the 1990s presumably led to sizable adjustment costs, which lowered both output growth and productivity growth. Fernald also pointed out that much about the role of IT in future growth is unknown at this point, raising questions such as, Will the rate of technical change slow? How elastic is the demand for IT? Will the relative price of IT goods continue to fall? What will happen in the non-IT sector, which accounts for 94 percent of the economy?

Skill-Biased Technological Change and Wage Inequality

The conference also included two papers about the role of technological advances in changes in inequality in the labor market. The authors examined whether inequality should be viewed as a causal result of skill-biased technological change or whether there is a missing link—or perhaps no link—between changes in technology and changes in wage inequality.

David H. Autor, Frank Levy, and Richard J. Murnane began by examining the contributions of changes in labor supply and labor demand to wage inequality during the 1940s through the 1990s. The authors discussed why computers increase the demand for more educated workers, arguing that computers have transformed the importance of manual versus cognitive tasks and routine versus nonroutine tasks. The data they used indicate that demand shifts are an important contributor to recent trends in inequality although supply shifts also exerted considerable influence during the entire period. The authors then explored several pieces of indirect evidence that computerization is responsible for the higher growth in relative demand for skilled workers during recent decades, including the timing of increases in computerization compared with the timing of the rise in wage inequality and trends in educational upgrading within industries.

Several puzzles emerge from Autor, Levy, and Murnane's paper, such as whether relative demand for skilled workers began accelerating during the 1970s or during the 1980s and why the growth in relative demand for skilled workers decelerated during the 1990s. As Donna Ginther's discussion noted, the major contribution of Autor, Levy, and Murnane's work is that it provides a mechanism by which computers and information technology could lead to skill-biased technological change.

David Card and John E. DiNardo, in a paper printed in this Review, examined whether the increase in wage inequality during the 1980s was caused by skill-biased technological change. They focused on the merits and limitations of the skill-biased technological change hypothesis, namely, that an increase in demand for skilled workers has led to an increase in wage dispersion between skilled and unskilled workers. Card and DiNardo noted that the supply of skilled workers has increased, so there must have been a more-than-offsetting change in demand to account for the observed rise in wage inequality during the 1980s. They investigated whether different aspects of the wage structure are consistent with the possibility that technical change underlies the changes in demand that must have occurred.

Card and DiNardo pointed out many inconsistencies that make it difficult to reconcile all of the observed trends with the skill-biased technological change hypothesis. As the discussion by Ginther noted, Card and DiNardo provide a good start at critically examining the skill-biased technological change hypothesis; however, she argued that it is an oversimplification to suggest that skill-biased technological change is a "unicausal" explanation for the many changes in the wage structure since 1980.

Technology and Productivity in the Firm

John Haltiwanger presented a paper that complements those by Autor, Levy, and Murnane and Card and DiNardo. The latter two papers used data on wage inequality from the perspective of workers while Haltiwanger's paper used data from wages on the establishment side.

Haltiwanger discussed the correlation between technology investments and wage dispersion and productivity dispersion, both of which increased since the 1980s. He found that both phenomena occurred at the between-plant, within-industry level, suggesting that the changes in economic forces were not industrywide but occurred at a more micro level. Another implication of Haltiwanger's findings is that workers have become more segregated by skill level, a proposition directly tested in a related paper by Lengermann (2001). Haltiwanger concluded that changes in plants' investments in computers and other forms of capital account for a substantial proportion of the increases in wage and productivity dispersion.

The discussion by Robert A. Eisenbeis cautioned that some of the paper's findings are sensitive to the time periods analyzed and that the empirical model

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2. Presentations included seven papers by distinguished economists, discussant comments on those papers, and speeches by Edward M. Gramlich, a member of the Board of Governors of the Federal Reserve System, and Alice M. Rivlin, a senior fellow at the Brookings Institution and former vice chair of the Federal Reserve Board. The entire conference proceedings, including the papers published in this *Economic Review,* will be published later this year by Kluwer Academic Publishers.

does not explain much of the wage and productivity dispersion between plants. Eisenbeis also noted that the role of macroeconomic cyclical forces versus secular changes is unclear.

Edward N. Wolff, in the final paper from the conference printed in this Review, used industry-level data to examine the relationships between productivity and the computerization, educational attainment, and skill levels of workers at the industry level. Perhaps surprisingly, he found no evidence that education is linked to productivity growth. However, cognitive skills—as measured by job-skill requirements from the *Dictionary of Occupational Titles*—are related to productivity growth, albeit modestly. Wolff's results also indicate that computers and related IT investments are not significantly associated with productivity growth at the industry level. Paula Stephan's discussion of Wolff's paper questioned whether the failure to find a relationship between computerization and productivity would be robust to including data from the 1990s and whether other measures might better capture skill, particularly with regard to IT skills.

Kathryn Shaw investigated the roles of investment in IT and changes in human resource management practices in corporate performance. Using traditional case study techniques, Shaw documented the relationship between changes in human resource practices and productivity gains in the steel industry. The paper argues that IT lowers the costs of providing information to workers as well as greater problem-solving capacities on the part of skilled workers. In her discussion, Stephan noted that Shaw's paper makes an important contribution by linking the literature on IT and performance with the literature on workplace practices and performance.

The papers presented at the conference add to our understanding of the role of technological change in the economy, both in recent years and in the decades ahead.

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

DALE W. JORGENSON, MUN S. HO, AND KEVIN J. STIROH

Jorgenson is the Frederic Eaton Abbe Professor of Economics at Harvard University. Ho is a visiting scholar at Resources for the Future. Stiroh is a research officer at the New York Fed. *They thank John Fernald for helpful comments and Jon Samuels for excellent research assistance. The Bureau of Labor Statistics and the Bureau of Economic Analysis provided data and advice.*

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

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

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:

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

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

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.

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.

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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Information Technology and Productivity: Where Are We Now and Where Are We Going?

STEPHEN D. OLINER AND DANIEL E. SICHEL

The authors are an associate director and a senior economist, respectively, in the Division of Research and Statistics at the Federal Reserve Board. *They thank Darrel Cohen, John Fernald, Jaime Marquez, David Stockton, and conference participants for very useful comments and discussions. For extremely valuable help with data, they are grateful to Charlie Gilbert from the Federal Reserve Board, Bruce Grimm and David Wasshausen from the Bureau of Economic Analysis, and Michael Harper, Larry Rosenblum, and Steve Rosenthal from the Bureau of Labor Statistics. This paper draws heavily from the authors' earlier work, including text taken directly from Oliner and Sichel (2000a, b) and Sichel (1997).*

After a quarter-century of lackluster gains, the U.S. economy experienced a remarkable resurgence in productivity growth during the second half of the 1990s. From 1995 to 2000, output per hour in nonfarm business grew at an average annual rate of about 2½ percent compared with increases of only about 1½ percent per year from 1973 to 1995.[1] Our earlier work, along with other research, linked this improved performance to the information technology (IT) revolution that has spread through the U.S. economy.[2] Indeed, by 2000 this emphasis on the role of information technology had become the consensus view.

However, shortly after this consensus emerged, the technology sector of the economy went into a tailspin as demand for IT products fell sharply. Reflecting this retrenchment, stock prices for many technology firms collapsed, and financing for the sector dried up. These developments raised questions about the robustness of the earlier results that emphasized the role of information technology. They also cast some doubt on the sustainability of the rapid productivity growth in the second half of the 1990s. Nonetheless, the recent data remain encouraging. Productivity gains have continued to be strong, with output per hour rising 2 percent over the four quarters of 2001—a much larger increase than is typical during a recession.

Against the backdrop of these developments, much effort has been devoted to estimating the underlying trend in productivity growth (see, in particular, Baily 2002; DeLong 2002; Gordon 2002; Jorgenson, Ho, and Stiroh 2002; Kiley 2001; Martin 2001; McKinsey Global Institute 2001; and Roberts 2001). For the most part, these papers take a relatively optimistic view of the long-run prospects for productivity growth.

We add to this literature in two ways. First, to assess the robustness of the earlier evidence on the role of information technology, we extend the growth-accounting results in Oliner and Sichel (2000a) through 2001. These results continue to support the basic story in our earlier work; namely, the data still show a substantial pickup in labor productivity growth and indicate that both the *use* of information technology and efficiency gains associated with the *production* of information technology were central factors in that resurgence.

Second, to assess whether the pickup in productivity growth since the mid-1990s is sustainable, we analyze the steady-state properties of a multisector growth model. This exercise allows us to translate alternative views about the evolution of the technology sector (and other sectors of the economy) into "structured guesses" about future growth in labor productivity. As highlighted by Jorgenson (2001), the pace of technological progress in high-tech industries—especially semiconductors—likely will be a key driver of productivity growth going forward. Thus, we develop a model that is rich enough to trace out the aggregate effects of these driving influences. We view this steady-state machinery not as a forecasting model per se but rather as a tool for generating a likely range of outcomes for labor productivity growth over roughly the next decade. Beyond that horizon, the uncertainty about the structure and evolution of the economy is too great for our steady-state approach to offer much insight.

Our structured guesses of labor productivity growth range from 2 percent to roughly 2³/₄ percent per year. The lower end of the range reflects conservative assumptions for key parameters in our model. Notably, in this scenario, we assume that the rate of technological advance in the semiconductor industry drops back to its historical average from the extremely fast pace in the second half of the 1990s and that the semiconductor and other IT sectors fail to grow any further as a share of (current-dollar) economic activity. In contrast, to generate the upper end of the range, we assume that the pace of technological advance in the semiconductor sector reverts only halfway to its historical average and that the various IT sectors continue to grow as a share of the economy. Of course, much uncertainty attends this exercise, and we also discuss more extreme scenarios in which labor productivity growth in the steady state would fall short of 2 percent or would exceed 3 percent. We believe, however, that these more extreme alternatives are less likely to occur than the scenarios generating labor productivity growth in the 2 to 2³/₄ percent range. This range, which includes the pace recorded over the second half of the 1990s, puts us squarely in the camp of those who believe that a significant portion—and possibly all—of the mid-1990s' productivity resurgence is sustainable.

The pace of technological progress in high-tech industries—especially semiconductors—likely will be a key driver of productivity growth going forward.

The next section of the paper provides a largely nontechnical overview of the analytical framework. Next, we briefly discuss the data we use and then describe the growth-accounting results extended through 2001. We continue by laying out the alternative steady-state scenarios that we analyze and then present the steady-state results. Appendix 1 fully describes our multisector model and derives all the theoretical results that underlie our growth-accounting and steady-state estimates. Appendix 2 provides detailed documentation for each data series used in the paper.

Analytical Framework

This paper employs the neoclassical growth-accounting framework pioneered by Solow (1957) and used extensively by researchers ever since.[3] The neoclassical framework decomposes the growth in labor productivity, measured by output per hour worked, into the contributions from three broad factors: increases in the amount of capital per hour worked (usually referred to as capital deepening), improvements in the quality of labor and growth in multifactor productivity (MFP). MFP is the residual in this framework, capturing improvements in the way that firms use their capital and labor but also embedding any errors in the estimated contributions from capital deepening and labor quality.

The growth-accounting framework can be tailored to address many different issues. We employ it to assess the growth contribution from IT capital, taking account of both the use of this capital throughout the economy and the efficiency gains realized in its production. Given this focus, we construct a model of the nonfarm business economy that highlights key IT-producing industries. Our model, which extends the two-sector models developed in Martin (2001) and Whelan (2001), divides nonfarm business into five sectors. Three sectors produce final IT goods—computer hardware, software, and communication equipment—and a large non-IT sector produces all other final goods and services. The fifth sector in the model produces semiconductors, which are either consumed as an intermediate input by the final-output sectors or exported to foreign firms. To focus on the role of semiconductors in the economy, the model abstracts from all other intermediate inputs.

Our model relies on several assumptions that are typically imposed in growth-accounting studies. In particular, we assume that all markets are perfectly competitive and that production in every sector is characterized by constant returns to scale. Labor and capital are assumed to be completely mobile, an assumption that implies a single wage rate for labor across all sectors and a single rental rate for each type of capital. Within this competitive market structure, we assume that firms set their investment and hiring decisions to maximize profits. Moreover, when firms purchase new capital or hire additional workers, we assume they do not incur any adjustment costs that would reduce output while these new inputs are integrated into the firms' production routines. Finally, we do not explicitly model cyclical changes in the intensity with which firms use their capital and labor.

These assumptions yield a tractable analytical framework by abstracting from some notable features of the actual economy. One could be concerned that these assumptions are so restrictive as to distort the empirical results. In consideration of these concerns, we would not advocate using a framework like ours to decompose year-to-year changes in productivity growth because cyclical factors omitted from the model could substantially affect the results. However, Basu, Fernald, and Shapiro (2001) showed that the basic characterization of productivity trends in the 1990s remains intact even after allowing for adjustment costs, nonconstant returns to scale, and cyclical variations in the use of capital and labor.

With this background, we now discuss the key analytical results from our model. The rest of this section presents and interprets these results; formal derivations can be found in Appendix 1.

Growth in aggregate labor productivity. As shown in the first proposition of Appendix 1, our model yields a standard decomposition of growth in aggregate labor productivity. Let $\dot{Z}$ denote the growth rate of any variable Z. Then, the growth of output per hour for nonfarm business as a whole can be written as

$$(1)\quad \dot{Y}-\dot{H}=\alpha_C^K(\dot{K}_C-\dot{H})+\alpha_{SW}^K(\dot{K}_{SW}-\dot{H})+\alpha_M^K(\dot{K}_M-\dot{H}) + \alpha_O^K(\dot{K}_O-\dot{H})+\alpha^L\dot{q}+\dot{MFP} = \sum_{j=1}^{4}\alpha_j^K(\dot{K}_j-\dot{H})+\alpha^L\dot{q}+\dot{MFP},$$

where Y denotes nonfarm business output in real terms; H denotes hours worked in nonfarm business; K_C, K_{SW}, K_M, and K_O denote the services provided by the stocks of computer hardware, software, communication equipment, and all other tangible capital, respectively; and q denotes labor quality. The α terms are income shares; under the assumptions of our model, the income share for each input equals its output elasticity, and the shares sum to 1. The second line of equation 1 merely rewrites the decomposition with more compact notation, where j indexes the four types of capital.[4]

Equation 1 shows that growth in labor productivity reflects capital deepening, improvements in labor quality, and gains in MFP, with the overall growth contribution from capital deepening constructed as the sum of the contributions from the four types of capital. Each such contribution equals the increase in that type of capital per work hour, weighted by the income share for that capital. This decomposition is entirely standard and matches the one used in Oliner and Sichel (2000a, b). Note that equation 1 does not identify the sectors using capital and labor; all that matters is the aggregate amount of each input. Under our assumptions, we need not keep track of the individual sectors because each type of capital has the same marginal product regardless of where it is employed, and the same holds for labor. Hence, transferring capital or labor from one sector to another has no effect on labor productivity for nonfarm business as a whole.

Our growth-accounting decomposition depends importantly on the income shares of the various types of capital. These income shares are not directly observable, and we estimate them in accordance with the method used by the Bureau of Labor Statistics. In this framework, the income share for capital of type j is

$$(2)\quad \alpha_j = (R + \delta_j - \Pi_j)T_j p_j K_j / pY,$$

where R is a measure of the nominal net rate of return on capital, which is the same for all types of capital under our assumption of profit maximization

1. This paper was already in production at the time of the July 2002 annual revision of the National Income and Product Accounts (NIPAs), and all numbers in the paper refer to the prerevision data. Had we been able to take the revision into account, the basic story of the paper would remain intact although productivity growth and high-tech capital deepening in recent years would be a bit lower than the figures we present.
2. See Oliner and Sichel (2000a), Bosworth and Triplett (2000), Brynjolfsson and Hitt (2000), Jorgenson and Stiroh (2000), Jorgenson (2001), and Whelan (2000). For a more skeptical view of the role of information technology written at that time, see Gordon (2000).
3. See Steindel and Stiroh (2001) for an overview of growth accounting, issues related to the measurement of productivity, and trends in productivity growth in the postwar period.
4. Time subscripts on both the income shares and the various growth rates have been suppressed to simplify the notation. We use log differences to measure growth rates. The income share applied to a log difference between periods t and $t + 1$ is measured as the average of the shares in these two periods.

and full capital mobility; δ_j is the depreciation rate for capital of type j; Π_j measures any expected change in the value of this capital over and above that captured in the depreciation rate; T_j is a composite tax parameter; p_jK_j is the current-dollar stock of this capital; and pY is total current-dollar income in the nonfarm business sector. The intuition behind equation 2 is straightforward. In a competitive market, each dollar of type j capital must earn a gross annual return that covers the net return common to all capital as well as the loss of value that this capital suffers over the year and the taxes imposed on the income it generates. The product of this gross return and the current-dollar stock equals

In addition to explaining the source of the productivity pickup in the 1990s, we wish to estimate a plausible range for productivity growth in the future.

the current-dollar income assumed to be earned by type j capital, which we divide by total income in nonfarm business to obtain the desired income share. Once we calculate each capital share in this way, the labor share is simply one minus the sum of the capital shares.

Aggregate and sectoral MFP growth. The term for aggregate MFP growth in equation 1 can be decomposed into the contributions from MFP growth in each sector. In particular, proposition 1 in the model appendix shows that

$$(3)\quad \dot{MFP} = \sum_{i=1}^{4} \mu_i \dot{MFP_i} + \mu_S \dot{MFP_S},$$

where i indexes the four final-output sectors, s denotes the semiconductor sector, and the μ term for each sector represents its output expressed as a share of total nonfarm business output in current dollars. This sectoral weighting scheme was initially proposed by Domar (1961) and formally justified by Hulten (1978). The Domar weights sum to more than one, an outcome that may seem odd at first glance.[5] However, this weighting scheme is needed to account for the production of intermediate inputs. Without this "gross-up" of the weights, the MFP gains achieved in producing semiconductors (the only intermediate input in our model) would be omitted from the decomposition of aggregate MFP growth.

To see this point more clearly, note that equation 3 can be rewritten as

$$(4)\quad \dot{MFP} = \sum_{i=1}^{4} \mu_i [\dot{MFP_i} + \beta_i^S (1+\theta) \dot{MFP_S}],$$

where $1 + \theta$ equals the ratio of domestic semiconductor output to domestic use of semiconductors and β_i^S denotes semiconductor purchases by final-output sector i as a share of the sector's total input costs. This result, derived in proposition 2, shows that the semiconductor sector, in effect, can be vertically integrated with the final-output sectors that it supplies. MFP growth in each vertically integrated sector—the term in brackets—subsumes the MFP gains at its dedicated semiconductor plants. Thus, equation 4 shows that the Domar weighting scheme (in equation 3) can be viewed as aggregating MFP growth from these vertically integrated sectors.

To make use of equation 3, we need to estimate MFP growth in each sector of our model. We do this with the so-called dual method employed by Triplett (1996) and Whelan (2000), among others. This method uses data on the prices of output and inputs, rather than their quantities, to calculate sectoral MFP growth. We opt for the dual approach because the required data are more readily available.

The basic intuition behind the dual approach can be explained with an example involving semiconductors, the prices of which have trended down sharply over time. To keep the example simple, assume that input prices for the semiconductor sector have been stable. Given the steep decline in semiconductor prices relative to the prices for other goods and services, MFP growth at semiconductor producers must be rapid compared to that elsewhere. Were it not, semiconductor producers would be driven out of business by the ever-lower prices for their output in the face of stable input costs. This example illustrates that relative growth rates of sectoral MFP can be inferred from movements in relative output prices.[6]

We rely on this link to estimate sectoral MFP growth. Proposition 3 provides the details, which involve some messy algebra. Roughly speaking, each sectoral MFP growth rate can be written as

$$(5)\quad \dot{MFP_i} = \dot{MFP_o} - \pi_i + \text{terms for the relative growth in sectoral input costs},$$

where $\pi_i \equiv (\dot{p}_i - \dot{p}_o)$ denotes the difference in output price inflation between sector i and the "other final-output" sector, which serves as our benchmark sector. If input costs grew at the same rate in every sector, the change in relative output prices would fully characterize the differences in sectoral MFP growth. However, because semiconductors loom large in the cost structure of the computer industry, we know that input costs for that industry are falling relative to those for other sectors. The additional terms in equation 5 take account of these differences in sectoral input costs.

Note that equation 5 determines relative rates of MFP growth, not the absolute rate in any sector. We pin down the absolute MFP growth rates in two different ways, the first of which uses equation 3 to force the sectoral MFP growth rates to reproduce our estimate of aggregate MFP growth. This case represents the methodology we use to compute historical growth contributions through 2001. In the second case, which we use for our steady-state analysis, we condition on an assumed pace of MFP growth in the "other final-output" sector, which generates the remaining sectoral MFP growth rates via equation 5 and aggregate MFP growth via equation 3.

Analysis of the steady state. In addition to explaining the source of the productivity pickup in the 1990s, we wish to estimate a plausible range for productivity growth in the future. To develop such a range, we impose additional steady-state conditions on our model, closely following the two-sector analysis in Martin (2001) and Whelan (2001).

Among the conditions imposed to derive steady-state growth, we assume that output in each sector grows at a constant rate (which differs across sectors). In addition, we impose conditions that are sufficient to force investment in each type of capital to grow at the same (constant) rate as the stock of that capital. Taken together, these conditions can be shown to imply that production in each final-output sector grows at the same (constant) rate as the capital stock that consists of investment goods produced by that sector. Two other important conditions are that labor hours grow at the same (constant) rate in each sector and that all income shares and sectoral output shares remain constant.

Under these steady-state conditions, proposition 4 shows that the growth-accounting equation for aggregate labor productivity becomes

$$(6)\ \dot{Y}-\dot{H}=\sum_{i=1}^{4}(\alpha_i^K/\alpha^L)(\dot{MFP}_i+\beta_i^S\,\dot{MFP}_S)+\dot{q}+\dot{MFP},$$

where $\dot{MFP}$ is calculated, as above, from equation 3. Note that equation 6 contains no explicit terms for capital deepening, in contrast to its non-steady-state counterpart, equation 1. No such terms appear because the steady-state pace of capital deepening is determined endogenously within the model as a function of the sectoral MFP growth rates. Hence, the summation on the right side of equation 6 represents the growth contribution from this induced capital deepening. With this interpretation, it becomes clear that equations 1 and 6 share a common structure: Both indicate that the growth of labor productivity depends on capital deepening, improvements in labor quality, and growth in MFP.

To further interpret equation 6, consider the growth-accounting equation (outside the steady state) for a simple one-sector model:

$$(7)\ \dot{Y}-\dot{H}=\alpha^K(\dot{K}-\dot{H})+\alpha^L\dot{q}+\dot{MFP}.$$

Now impose the steady-state condition that output and capital stock grow at the same rate and substitute $\dot{K}=\dot{Y}$ into equation 7, noting that $\alpha^K+\alpha^L=1$ under constant returns to scale. The result is

$$(8)\ \dot{Y}-\dot{H}=\dot{q}+\dot{MFP}/\alpha^L=(\alpha^K/\alpha^L)\dot{MFP}+\dot{q}+\dot{MFP},$$

5. It is easy to see that the weights sum to more than one if semiconductor producers sell all of their output to the four final-output sectors, with none sold as exports. In this case, semiconductors are strictly an intermediate input, and production by the four final-output sectors accounts for all nonfarm business output. Hence, the μ terms for these sectors sum to one before adding in μ_S. With a little algebra, one can show that the μ terms also sum to more than one in the more general case that allows for exports of semiconductors.

6. Under perfect competition, the growth rate of MFP in each sector can be inferred exactly from relative price movements. However, if markets are not perfectly competitive, then the dual methodology would yield an inaccurate reading on MFP growth to the extent that relative price changes resulted from swings in margins rather than technological developments. Of course, if there is imperfect competition but margins are constant, then MFP growth rates still can be inferred exactly from relative price movements because changes in margins would not be a source of changes in relative prices. For the semiconductor sector—where market concentration in microprocessors suggests that this potential problem with the dual methodology could be particularly acute—Aizcorbe (2002) found that a conventional Tornquist index of Intel microprocessor prices fell 24½ percent per quarter on average from 1993 to 1999; adjusted for movements in Intel's margins over this period, the index declined 21 percent per quarter. Thus, swings in margins appear to have had a relatively small average effect on chip prices over this period.

where the second equality uses the fact that $(\alpha^K / \alpha^L) = (1/\alpha^L) - 1$ when $\alpha^K + \alpha^L = 1$. Comparing equations 6 and 8 shows that our steady-state growth-accounting decomposition is the multisector counterpart to the decomposition in a one-sector model.

Summary. We use equations 1–3 and 5 to decompose the observed growth in labor productivity through 2001. Equation 1 provides the structure for the decomposition, while equation 2 shows how we calculate the income shares, and equations 3 and 5 (implemented with the dual method) show how we relate aggregate MFP growth to its sectoral components. To estimate the growth of labor productivity in the steady state, we replace equation 1 with equation 6, but otherwise we use the same machinery as for the historical decompositions.

Are the results from earlier research that emphasized the role of information technology still valid given the sharp contraction in the technology sector?

Data

This section provides a brief overview of the data used for this paper; a detailed description appears in Appendix 2. To estimate the decomposition of labor productivity growth, we rely heavily on data from the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS). Our starting point is the data set assembled by the BLS for its estimates of multifactor productivity. These annual data cover the private nonfarm business sector in the United States and provide measures of the growth of real output, real capital input, labor hours, and labor quality. At the time we were writing, the BLS data set ran through 2000, and we extended all necessary series through 2001.

The income shares in our growth-accounting calculations depend on estimates of the gross rate of return earned by each asset $(R + \delta_j - \Pi_j)$. To measure the components of the gross return, we rely again on data from the BEA and BLS. With just a few exceptions, the depreciation rates (δ_j) for the various types of equipment, software, and structures are those published by the BEA. Because the BEA provides only limited information on the depreciation rates for components of computers and peripheral equipment, we follow Whelan (2000) and set these depreciation rates equal to a geometric approximation calculated from BEA capital stocks and investment flows. For personal computers, we are uncomfortable with the BEA's procedure and instead set the depreciation rate for PCs equal to the 30 percent annual rate for mainframe computers. (See Appendix 2 for a discussion of this issue.) To estimate the capital gain or loss term in the gross return (Π_j), we use a three-year moving average of the percent change in the price of each asset. The moving average smooths the often volatile yearly changes in prices and probably conforms more closely to the capital gain or loss that asset owners expect to bear when they make investment decisions. Finally, to calculate the net return (R), we mimic the BLS procedure, which computes the average realized net return on the entire stock of equipment, software, and structures. By using this average net return in the income share for each asset, we impose the neoclassical assumption that all types of capital earn the same net return in a given year.

To implement the sectoral model of MFP, we need data on final sales of computer hardware, software, and communication equipment as well as data on the semiconductor sector. Our data on final sales of computer hardware came from the NIPAs, and we used unpublished BEA data to calculate final sales of software and communication equipment. For the semiconductor sector, we used data from the Semiconductor Industry Association as well as data constructed by Federal Reserve Board staff to support the Fed's published data on U.S. industrial production.

Decomposition of Labor Productivity Growth

As discussed above, our earlier research documented that information technology was a key driver behind the resurgence in labor productivity growth during the second half of the 1990s. Recent developments—including the bursting of the Nasdaq bubble and the dramatic retrenchment in the high-tech sector—have raised questions about the robustness of those results. By extending our estimates through 2001, we can assess whether recent data still support the basic story in our earlier research. We describe our new numbers and then compare them to our earlier results.

Results through 2001. Table 1 presents our decomposition of labor productivity growth in the nonfarm business sector through 2001. As shown in the first line of the table, growth in labor productivity picked up from about 1.5 percent per year in the first half of the 1990s to about 2.4 percent since

TABLE 1

Contributions to Growth in Labor Productivity, Using Data as of March 2002

		1974–90 (1)	1991–95 (2)	1996–2001 (3)	Post-1995 change (3) minus (2)
1.	Growth of labor productivity[1]	1.36	1.54	2.43	.89
	Contributions from[2]				
2.	Capital deepening	.77	.52	1.19	.67
3.	Information technology capital	.41	.46	1.02	.56
4.	Computer hardware	.23	.19	.54	.35
5.	Software	.09	.21	.35	.14
6.	Communication equipment	.09	.05	.13	.08
7.	Other capital	.37	.06	.17	.11
8.	Labor quality	.22	.45	.25	–.20
9.	Multifactor productivity	.37	.58	.99	.41
10.	Semiconductors	.08	.13	.42	.29
11.	Computer hardware	.11	.13	.19	.06
12.	Software	.04	.09	.11	.02
13.	Communication equipment	.04	.06	.05	–.01
14.	Other sectors	.11	.17	.23	.06
15.	Total IT contribution[3]	.68	.87	1.79	.92

[1] In the nonfarm business sector, measured as the average annual log difference for the years shown multiplied by 100.
[2] Percentage points per year.
[3] Equals the sum of lines 3 and 10–13.
Note: Detail may not sum to totals because of rounding.
Source: Authors' calculations based on BEA and BLS data

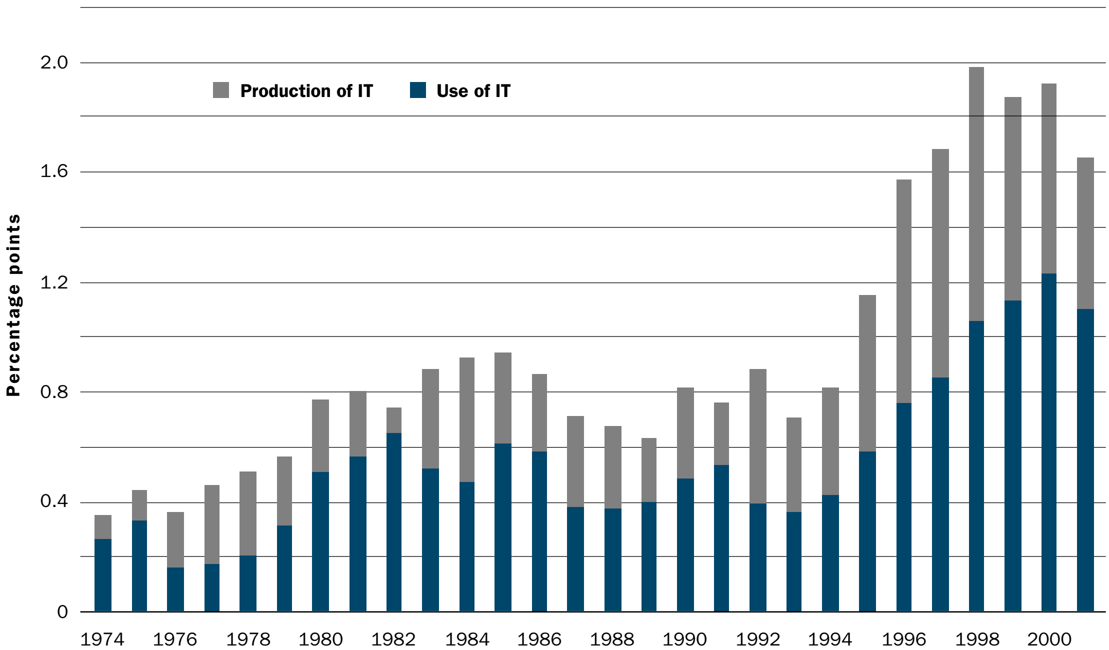
1995.[7] Rapid capital deepening related to information technology capital—the greater *use* of information technology—accounted for about three-fifths of this pickup (line 3). Other types of capital (line 7) made a much smaller contribution to the acceleration in labor productivity, while the contribution from labor quality actually fell across the two periods. Multifactor productivity (line 9) is left to account for a little less than half of the improvement in labor productivity growth.

Next, we decompose this overall MFP contribution into its sectoral components in order to estimate the growth contribution from the *production* of information technology. Lines 10–14 of Table 1 display this sectoral decomposition. The results show that the MFP contribution from semiconductor producers (line 10) jumped after 1995. Given our use of the dual methodology, this pickup owes to the more rapid decline in semiconductor prices in this period, which the model interprets as a speedup in MFP growth.

7. Note that the figures for output per hour in Table 1 are based on the BLS published series for nonfarm business output. This series is a product-side measure of output, which reflects spending on goods and services produced by nonfarm businesses. Alternatively, output could be measured from the "income side" as the sum of payments to capital and labor employed in that sector. Although the two measures of output differ only slightly on average over long periods of time, a sizable gap has emerged in recent years. By our estimates, the acceleration in the income-side measure was about one-third percentage point greater (at an average annual rate) after 1995. We employ the published product-side data to maintain consistency with other studies; in addition, if an adjustment were made to output and labor productivity growth, it is not clear how that adjustment should be allocated among the components of capital deepening and MFP growth. Nonetheless, the true pickup in productivity growth after 1995 could be somewhat larger than shown in our table.

CHART 1

Contributions from the Use and Production of Information Technology to Growth of Labor Productivity in Nonfarm Business



Source: Authors' calculations based on BEA, BLS, and other data

In contrast, the MFP contribution from the other information technology sectors taken together (lines 11–13) rose only a little after 1995 compared with the first half of the 1990s.

For computer hardware, the particularly rapid decline in prices after 1995 might have led one to believe that MFP growth in this sector had increased dramatically. However, as indicated earlier, the computer sector—as we define it—excludes the production of the semiconductors embedded in computer hardware. Thus, MFP in the computer sector represents only efficiency gains in the design and assembly of computers, not in the production of the embedded semiconductors. Accordingly, our results indicate that the faster declines in computer prices after 1995 largely reflected the sharp drop in the cost of semiconductor inputs rather than independent developments in computer manufacturing.

The MFP contributions from the software and communication equipment sectors were fairly small during both the 1991–95 and 1996–2001 periods. According to the published numbers, the relative prices of both software and communication equipment fell much less rapidly than did relative computer prices during these periods.[8] In addition, for communication equipment, our numbers indicate that much of the relative price drop that did occur reflected the plunging costs of semiconductor inputs, which our sectoral decomposition attributes to MFP growth in the semiconductor industry, not in communication equipment. Thus, the dual methodology suggests that the MFP gains in both software and communication equipment have been smaller than those in the computer sector.

Putting together the information technology pieces (line 15), greater use of information technology and faster efficiency gains in the production of IT capital goods more than accounted for the 0.89 percentage point speedup in labor productivity growth after 1995. This large contribution can also be seen in Chart 1; the blue bars show the contribution from the use of IT and the gray bars show the contribution from the production of IT on a year-by-year basis. As the chart shows, these contributions surged after 1994. Although they dropped back in 2001, the contributions for that year remain well above those observed before 1995. Based on these results, we conclude that recent data confirm the main findings in our earlier work. Namely, the resurgence in labor productivity is still quite evident in the data, and information technology appears to have played a central role in this pickup.

Further comparison to our earlier work. Table 2 compares our latest numbers to those in

TABLE 2

Acceleration in Labor Productivity between 1991–95 and Post–1995 Period, Effect of New Data and Revisions

	Oliner and Sichel (2000a) through 1999	This paper through 2000	This paper through 2001
1. Acceleration in labor productivity[1]	1.04	1.00	.89
Contributions from[2]			
2. Capital deepening	.48	.57	.67
3. Information technology capital	.45	.54	.56
4. Computer hardware	.36	.36	.35
5. Software	.04	.13	.14
6. Communication equipment	.05	.07	.08
7. Other capital	.03	.02	.11
8. Labor quality	–.13	–.20	–.20
9. Multifactor productivity	.68	.62	.41
10. Semiconductors	.27	.30	.29
11. Computer hardware	.10	.06	.06
12. Other sectors[3]	.31	.26	.06

[1] In the nonfarm business sector, measured as percentage points per year.
[2] Percentage points per year.
[3] Includes producers of communication equipment and software.
Note: Detail may not sum to totals due to rounding.
Source: Authors' calculations based on BEA and BLS data

Oliner and Sichel (2000a).[9] The first column of the table shows contributions to the pickup in labor productivity growth from our earlier paper, the second column presents estimates through 2000 using recent data, and the third column repeats the contributions through 2001 shown in Table 1. In addition to the inclusion of data for 2000, the numbers in the second column differ from those in the first because of data revisions since our earlier results were completed.[10] Clearly, incorporating data for 2000 and revisions for earlier years changed our results relatively little. The contribution to the productivity pickup from software capital deepening increased, but this increase was offset by a more negative

8. Jorgenson and Stiroh (2000) raised the possibility that software prices may have fallen faster than reported in the official numbers. While this speculation may be correct, software has historically been a craft industry, in which highly skilled professionals write code line by line. In the 1960s and 1970s, several studies examined costs per line of code written. Phister (1979, 502) estimated a 3.5 percent annual reduction in the labor required to produce one thousand lines of code. Zraket (1992) argued that the nominal cost per line of code in the early 1990s was little changed from twenty years earlier, a scenario that would yield a real decline similar to Phister's. Of course, the more recent adoption of software suites, licenses, and enterprisewide software solutions may well have led to dramatic declines in the effective price of software. All told, we believe that considerable uncertainty still attends the measurement of software prices.

   Jorgenson and Stiroh (2000) also suggested that prices of communication equipment may have fallen faster than reported in official statistics. Recent work by Doms (2002) provides support for that perspective.
9. Table 2 shows separate MFP contributions only for the semiconductor and computer sectors to maintain comparability with our earlier work.
10. The most important data revisions that we factored in were the July 2000 and July 2001 NIPA revisions released by the BEA (which are fully reflected in the latest BLS multifactor productivity data) and the official published estimates of capital stocks for software. (In our earlier work, we had included our own estimate of software capital stocks.) In addition, we have made some minor adjustments to our estimation procedures, but these changes had relatively small effects.

contribution from labor quality and a somewhat smaller contribution from MFP growth.

Extending the results through the recession year 2001 tempers the step-up in labor productivity growth (line 1), as would be expected given the procyclical behavior of productivity gains. At the same time, line 2 indicates that the growth contribution from capital deepening increased with the inclusion of data for 2001. The large implied contribution in 2001 may seem puzzling in light of the recession-related downturn in investment spending. However, recall that capital deepening reflects the ratio of capital services to hours worked. The decline in hours in 2001, other things being equal, boosts the capital-hours ratio. Also, note that our growth accounting uses annual-average data. Because investment spending weakened over the course of 2001, annual averaging smooths this decline relative to the change observed over the four quarters of the year. Similarly, the Tornquist weighting procedure delays the impact of such changes by using an average of this year's and last year's capital income shares as aggregation weights for the capital deepening contributions. Thus, some of the effects of the recession on corporate profits (and hence on the capital income shares) will not show up in our numbers until 2002. Indeed, a back-of-the-envelope calculation suggests that the contribution of capital deepening will drop back in 2002.[11]

Some observers might argue that the very small acceleration of MFP outside the IT-producing sectors indicates that the productivity benefits of IT have been either narrowly focused or have been largely reversed over the past year.

The final effect of folding in data for 2001 is the noticeably smaller contribution of MFP to the post-1995 step-up in labor productivity growth (line 9). Virtually the entire downward revision is in the large residual sector consisting of all nonfarm business except the computer and semiconductor industries (line 12).

Some observers might argue that the very small acceleration of MFP outside these IT-producing sectors indicates that the productivity benefits of IT have been either narrowly focused or have been largely reversed over the past year. However, we are not inclined to accept either interpretation for two reasons. First, the use of IT throughout the economy has contributed significantly to the pickup in labor productivity growth, quite apart from developments in IT-producing industries. Second, the much-reduced MFP acceleration in other industries likely reflected cyclical factors.[12] Identifying the magnitude of such cyclical influences is challenging, and we believe that the trend cannot be inferred from the average growth rate between 1995 and 2001. The first year of that period, 1995, was midway through the cycle, while the last year, 2001, was a recession year.[13] Thus, taking an average over the 1995–2001 period implicitly draws a line from a point at midcycle to a point near the bottom of the cycle. Such a line likely understates the trend over this period.

Labor Productivity Growth in the Steady State

How much of the resurgence in labor productivity growth in the second half of the 1990s is sustainable? To address this question, we use the steady-state machinery described earlier to generate a range of likely outcomes for labor productivity growth in the future. We do not regard these steady-state results as forecasts of productivity growth for any particular time period. Rather, this exercise yields structured guesses of the sustainable growth in labor productivity consistent with alternative scenarios for the evolution of key features of the economy.

To construct this range of likely outcomes, we set lower and upper bounds on steady-state parameters and then solve for the implied rates of labor productivity growth. We believe that these scenarios encompass the most plausible paths going forward, but there is substantial uncertainty about future productivity developments. Hence, as we will discuss, the sustainable pace of labor productivity growth could fall outside the range that we consider most likely. The rest of this section describes the lower- and upper-bound parameter values that we chose, presents our steady-state results, and compares our results to those obtained by other researchers.

Parameter values. Table 3 displays the many parameters that feed into our model of steady-state growth. To provide some historical context, the first three columns of the table show the average value of each parameter over the 1974–90, 1991–95, and 1996–2001 periods. The next two columns present our assumed lower-bound and upper-bound values for each parameter in the steady state, and the final column briefly indicates the rationale for these steady-state values.[14]

Lines 1–15 of the table list the parameters needed to compute aggregate and sectoral MFP growth in the steady state. These parameters include each sector's current-dollar share of nonfarm business output (the μs), outlays for semiconductors as a share of total input costs in each final-output sector (the βs), the rate of output price inflation in each sector relative to that in the other-final-output sector (the πs), and the growth of MFP in the other-final-output sector (MFP_O).

Although the steady-state bounds for some of these parameters require no discussion beyond the brief rationale in the table, others need further explanation.[15] Starting with the output shares, we calibrated the steady-state bounds from the plots in Chart 2. The short lines in each panel represent the bounds, which can be compared to the history for each series. The current-dollar output shares for producers of computer hardware and communication equipment have each fluctuated in a fairly narrow range since the mid-1980s. Our steady-state bounds largely bracket those ranges. For producers of software and semiconductors, the current-dollar output shares have trended sharply higher over time, and our steady-state bounds allow for some additional increase from the average level in recent years.[16]

Among the semiconductor cost shares (the βs), we set the share for computers equal to 0.30, the middle of the range employed by Triplett (1996). For software, we set the share to zero. The share for communication equipment is shown in Chart 3. This share has risen quite a bit since the early 1990s, reflecting the increasing amount of computer-like technology in communication equipment. We set the steady-state bounds on the assumption that this trend will persist.

This increase in the semiconductor content of communication equipment implies that the relative price for such equipment is likely to fall more rapidly in the future than it has over history. We built that expectation into the steady-state bounds for π_M, shown on line 14. These values were chosen to ensure that the implied MFP growth rate for the sector, computed by the dual method, remained close to the average pace over 1996–2001.

This issue does not arise for other sectors, where the semiconductor cost shares are assumed to change little, if at all, going forward. For these sectors (lines 11–13), we set the bounds on relative price changes (the πs) by reference to historical patterns. The lower bound for each sector equals the average rate of relative price change over 1974–2001, while the upper bound lies midway between that average and the most rapid rate of relative price decline for the three subperiods since 1974. Thus, we do not assume that the extremely rapid declines in computer and semiconductor prices over 1996–2001 will persist in the steady state, even in our optimistic scenario.

How much of the resurgence in labor productivity growth in the second half of the 1990s is sustainable?

Lines 16–28 of the table list the components of the capital income shares. For the nominal rate of return on capital and the asset-specific depreciation

11. To show this, we calculated capital deepening for 2002 on the assumption that the growth rate of real investment in high-tech equipment snaps back to its robust average pace during 1996–2000 and that hours fall nearly 1 percent in 2002 on an annual average basis as projected in Macroeconomic Advisers' January 2002 *Economic Outlook*. Even under this optimistic assumption for investment and sluggish forecast for hours, the contribution of capital deepening to labor productivity growth in 2002 would be below its 2001 value (but still significantly above its pre-1995 value).
12. Even though MFP is often associated with technological change, short-run movements in MFP can be heavily influenced by cyclical factors that have little relation to technological change. For further discussion of this point, see Basu, Fernald, and Shapiro (2001).
13. Inferring the trend from the average growth rate between 1995 and 2000 also may be problematic because the average covers a period from midcycle to peak. Moving the initial year back to the prior peak in 1990 is not appealing because we are interested in what happened to productivity beginning in the mid-1990s.
14. Note that the upper-bound value for each parameter yields a higher rate of productivity growth than the lower-bound value. For some parameters, such as relative prices, the upper-bound value is numerically smaller than the lower-bound value.
15. In performing similar exercises, DeLong (2002), Kiley (2001), and Martin (2001) start with demand elasticities for high-tech products to generate output and income shares. In contrast, we set assumptions for output shares and other key parameters directly. Because relatively little is known about high-tech demand elasticities, we prefer the transparency of directly setting output shares and other parameters based on their historical patterns.
16. The output share for the semiconductor sector plunged in 2001 to the lowest level since 1994 owing to the deep cutbacks in spending on high-tech equipment during the recession. In setting the steady-state bounds, we assumed that the cyclical drop would be reversed as the economy recovers from recession.

TABLE 3

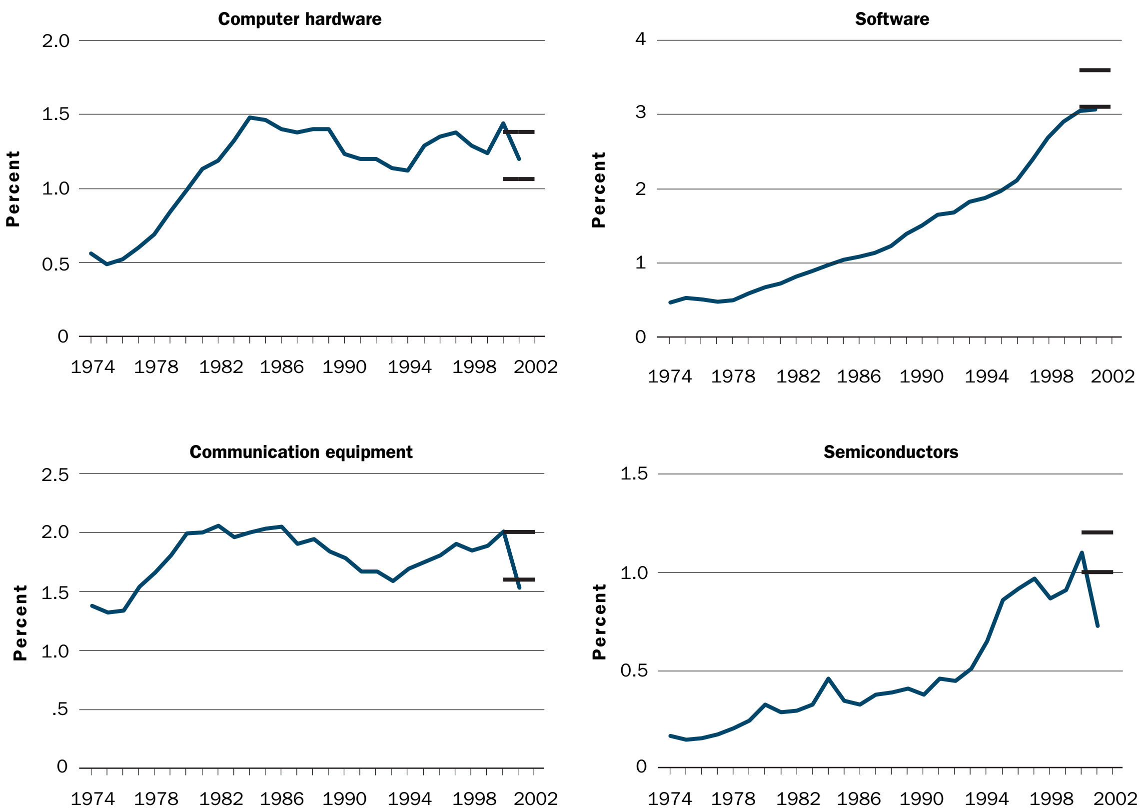
Parameter Values for Steady-State Calculations

Parameter	Historical averages 1974–1990	1991–1995	1996–2001	Steady-state values lower bound	upper bound	Method for setting steady-state values
Output shares[1] (μ)						
1. Computer hardware	1.06	1.19	1.32	1.10	1.40	See Chart 2.
2. Software	.84	1.79	2.70	3.10	3.60	See Chart 2.
3. Communication equipment	1.80	1.68	1.83	1.60	2.00	See Chart 2.
4. Other final-output sectors	96.33	95.45	94.14	94.20	93.00	Implied by lines 1–3 and 5.
5. Net exports of semiconductors	–.04	–.11	.00	.00	.00	1996–2001 average.
6. Total semiconductor output	.30	.58	.91	1.00	1.20	See Chart 2.
Semiconductor cost shares[1] (β)						
7. Computer hardware	30.00	30.00	30.00	30.00	30.00	Assumed constant value.
8. Software	.00	.00	.00	.00	.00	Assumed constant value.
9. Communication equipment	1.17	4.59	8.88	13.00	16.00	See Chart 3.
10. Other final-output sectors	.00	.27	.37	.46	.46	Implied by lines 1–4, 6–9, and 36.
Relative inflation rates[2] (π)						
11. Semiconductors	–28.90	–21.75	–44.71	–31.01	–37.86	Lower bound is 1974–2001 average; upper bound is midway between that value and fastest historical decline. (lines 11–13)
12. Computer hardware	–19.29	–17.79	–27.15	–20.71	–23.93	
13. Software	–4.13	–4.83	–3.90	–4.21	–4.52	
14. Communication equipment	–2.44	–4.06	–5.80	–6.00	–7.75	Calibrated to keep the sector's MFP growth rate near the 1996–2001 pace.
15. Growth of MFP_O[3]	.11	.17	.23	.11	.23	Used historical range.
16. Nominal return on capital[3] (R)	7.88	4.29	4.55	4.55	4.55	1996–2001 average.
Depreciation rates[3] (δ)						
17. Computer hardware	29.74	30.11	30.30	30.30	30.30	1996–2001 average.
18. Software	34.87	37.04	38.46	38.46	38.46	1996–2001 average.
19. Communication equipment	13.00	13.00	13.00	13.00	13.00	1996–2001 average.
20. Other business fixed capital	5.87	6.08	6.10	6.10	6.10	1996–2001 average.
Expected capital gains/losses[4] (Π)						
21. Computer hardware	–12.70	–11.79	–23.21	–17.50	–20.36	See footnote 5.
22. Software	3.27	–.56	–.31	–.44	–.50	See footnote 5.
23. Communication equipment	3.65	–.07	–3.01	–4.00	–5.75	See footnote 6.
24. Other business fixed capital	6.31	2.52	2.55	2.54	2.53	See footnote 5.
Capital-output ratios ($Tp_K K/pY$)						
25. Computer hardware	.0192	.0293	.0294	.0300	.0360	See Chart 4.
26. Software	.0191	.0440	.0618	.0800	.0900	See Chart 4.
27. Communication equipment	.0876	.1087	.0951	.0875	.1025	See Chart 4.
28. Other business fixed capital	2.4227	2.2648	2.1008	1.9000	2.0500	See Chart 4.
Income shares[1] (α)						
29. Computer hardware	.92	1.34	1.71	1.57	1.99	Implied. See Chart 5.
30. Software	.75	1.85	2.67	3.48	3.92	Implied. See Chart 5.
31. Communication equipment	1.48	1.88	1.96	1.89	2.39	Implied. See Chart 5.
32. Other business fixed capital	18.00	17.78	17.04	15.42	16.65	Implied. See Chart 5.
33. Other capital[7]	9.81	8.90	8.93	8.93	8.93	1996–2001 average.
34. Labor	69.04	68.25	67.69	68.72	66.13	Implied by lines 29–33.
Other parameters						
35. Growth of labor quality[3] (q)	.32	.65	.38	.30	.30	Assumed slower growth.
36. Ratio of domestic semiconductor output to domestic use ($1 + \theta$)	.89	.86	1.03	1.03	1.03	1996–2001 average.

1 Current-dollar shares, in percent.
2 Output price inflation in each sector minus that in the "other final-output" sector, in percentage points.
3 In percent.
4 Three-year moving average of price inflation for each asset, in percent.
5 Lower bound is average over 1991–2001; upper bound is midway between that value and the smaller of the 1991–95 and 1996–2001 values.
6 The lower and upper bounds equal the corresponding values for the relative inflation rate of communication equipment (line 14), plus 2 percentage points—the assumed rate of inflation in the "other final-output" sector.
7 Includes land, inventories, and tenant-occupied housing.

CHART 2

Current-Dollar Output Shares



Source: Authors' calculations based on BEA, BLS, and other data

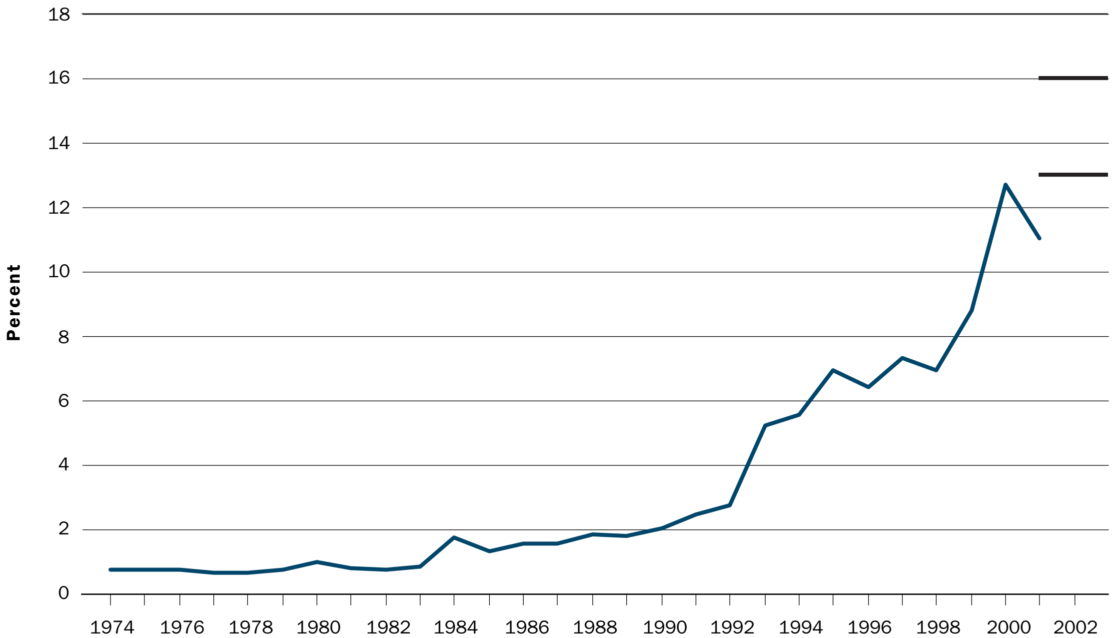
rates, we simply project forward the average values for 1996–2001. These parameters varied only slightly between the first and second halves of the 1990s; moreover, the higher nominal return on capital over 1974–90, which was driven in part by the elevated pace of inflation over that period, is not appropriate for the current low-inflation environment. For the next element of the income share, the expected capital gain or loss on the asset, we set the steady-state bounds in essentially the same way as we did for the relative inflation rates. For all types of capital except communication equipment, we chose these bounds by reference to the historical data, though we looked back only to 1991 to avoid building in the higher rates of inflation that prevailed over 1974–90. The bounds for communication equipment were set to the analogous bounds for the relative price decline on line 14, plus 2 percentage points. This add-on for the assumed rate of inflation in the other-final-output sector converts the relative price change into an absolute change.

The final piece of the income share is the (tax-adjusted) capital-output ratio, expressed in current dollars ($Tp_K K/pY$). Chart 4 displays this ratio back to 1974 for the four types of capital. For computer hardware and communication equipment, where the capital-output ratio has not displayed a clear trend of late, we set the bounds to keep the ratio in its neighborhood of recent years. In contrast, for software and other fixed capital, we chose the bounds to allow for a continuation of longer-term trends. Chart 5 shows the implied bounds for the capital income shares along with the historical series for these shares. The one series that bears comment is the share for other equipment and nonresidential structures, which plummeted in 2001 as the recession-induced decline in corporate profits depressed the nominal return to capital (R).[17] The steady-state bounds for this

17. The drop in R had a much greater effect on the income share for this broad capital aggregate than on the income shares for computers, software, or communication equipment. For these high-tech assets, the rapid trend rate of depreciation is the dominant piece of the gross return, overwhelming even sizable movements in R.

CHART 3

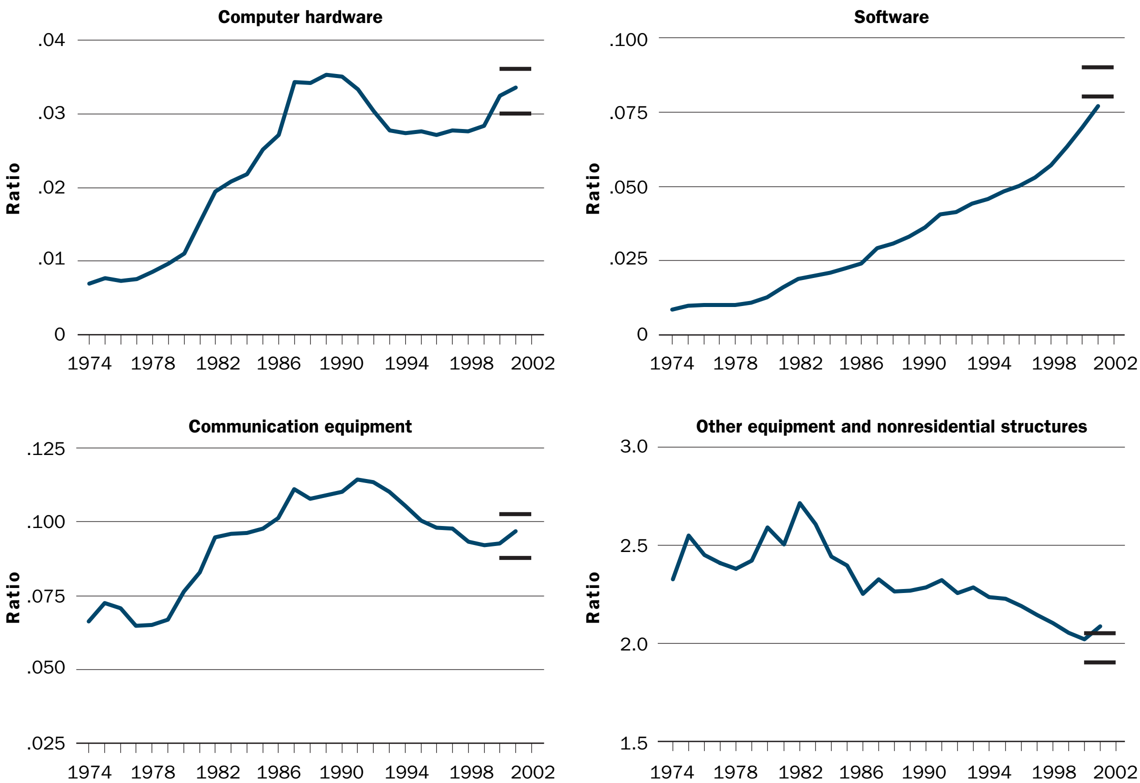
Semiconductor Cost Share in Communication Equipment



Source: Authors' calculations based on BEA, BLS, and other data

CHART 4

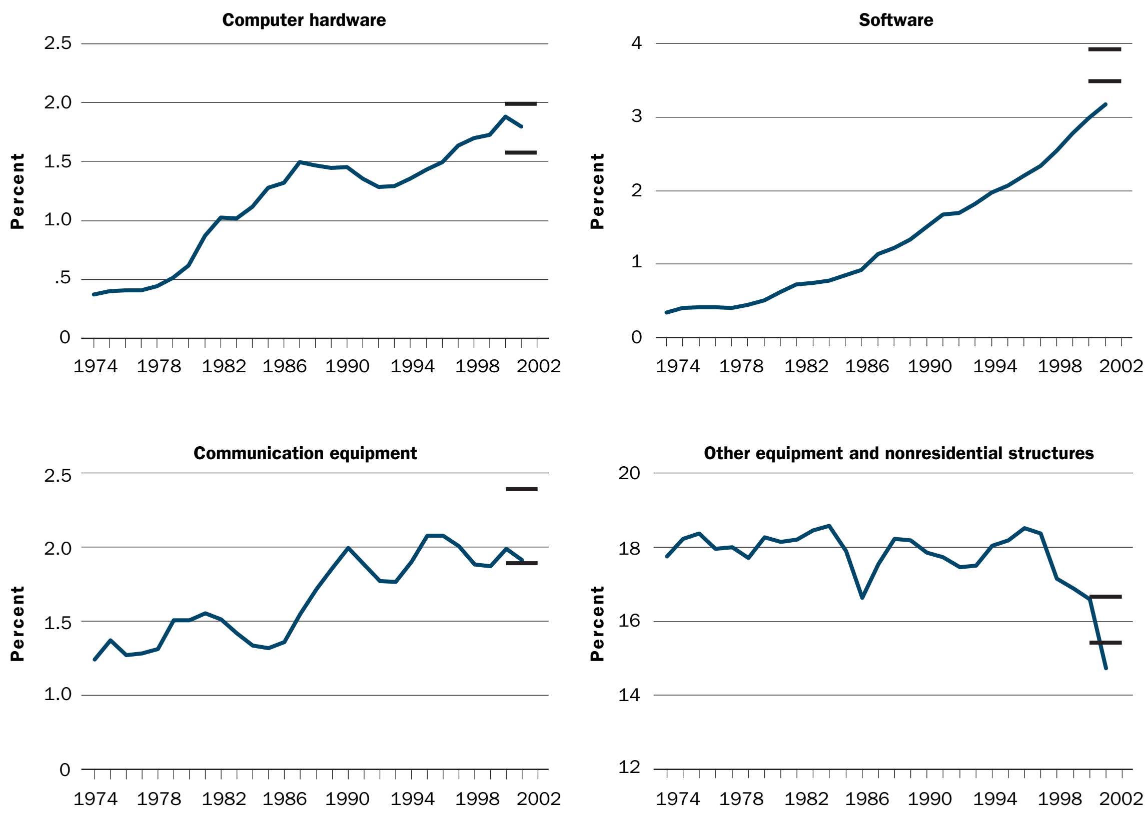
Current-Dollar Capital-Output Ratios



Note: Each subcomponent within a category is tax-weighted.
Source: Authors' calculations based on BEA, BLS, and other data

CHART 5

Current-Dollar Income Shares



Source: Authors' calculations based on BEA, BLS, and other data

income share imply at least a partial reversal of this cyclical decline.

The final parameter of note is the growth of labor quality (line 35). We assume that labor quality will increase 0.3 percent per year in the steady state, noticeably slower than its average annual rise over recent decades. Jorgenson, Ho, and Stiroh (2002) suggest a step-down in labor quality growth of similar magnitude while Aaronson and Sullivan (2001) project a slightly larger drop-off going forward.

Results. Table 4 contains the "structured guesses" of labor productivity growth in the steady state using lower-bound and upper-bound parameter values.[18] As shown on line 1, the lower-bound parameter values generate steady-state growth in labor productivity of about 2 percent while the upper-bound values imply growth of slightly more than 2¾ percent.[19] This range, which sits well above the sluggish pace realized from the early 1970s to the mid-1990s, suggests a relatively optimistic outlook for labor productivity.

To provide intuition for the steady-state range, note that the lower-bound figure of about 2 percent is roughly ½ percentage point below the pace of labor

18. As noted earlier, our model does not explicitly account for adjustment costs. Nevertheless, we recognize that such costs could have important implications for labor productivity growth, as emphasized by Kiley (2001) and Basu, Fernald, and Shapiro (2001). Implicitly, our steady-state estimates of labor productivity growth embed the average historical value of adjustment costs. Specifically, if adjustment costs have held down labor productivity growth on average historically, our growth-accounting framework will sweep these effects into the residual—which is MFP growth in "other final output." Because our steady-state estimates depend on MFP growth in that residual category, the average historical magnitude of adjustment costs is implicitly built into these estimates.

19. It is reassuring that the results generated by the steady-state model over historical periods are well aligned with measured productivity growth. In particular, if we use the steady-state model with the historical average parameter values in Table 3, it returns an average growth rate for labor productivity of 1.57 percent over 1974–2001, very close to the actual growth rate of 1.62 percent over this period.

TABLE 4

Steady-State Results

	Using lower-bound parameters	Using upper-bound parameters
1. Growth of labor productivity[1]	1.98	2.84
Contributions from[2]		
2. Induced capital deepening	.97	1.47
3. Information technology capital	.88	1.31
4. Other capital	.09	.16
5. Labor quality	.30	.30
6. Multifactor productivity	.72	1.07
7. Total IT contribution[3]	1.50	2.17

1 In the nonfarm business sector, measured in percent.
2 Percentage points per year.
3 Equals line 3 plus the contributions included in line 6 from producers of computer hardware, software, communication equipment, and semiconductors.
Note: Detail may not sum to totals because of rounding.

productivity growth during 1996–2001. This slowdown occurs because we assume that the rates of decline in semiconductor and computer prices revert to their long-run historical averages from the very rapid pace realized in the second half of the 1990s. These assumptions produce a marked slowdown in MFP growth in the semiconductor sector and, to a lesser extent, in the computer sector. Nonetheless, labor productivity growth for nonfarm business as a whole remains above the 1974–95 average because the IT sectors, taken together, constitute a larger part of the economy than they did in this earlier period.

The upper-bound figure of about 2.8 percent in the steady state is almost 1/2 percentage point above the 1996–2001 pace. The model generates this step-up even though the price declines for semiconductors and computers in the steady state (and hence the rates of MFP growth) are assumed to be less rapid than those in the second half of the 1990s. The countervailing factor is that the semiconductor sector and other IT sectors grow as a share of the economy compared to that period. The greater importance of these sectors with relatively fast MFP growth more than makes up for the slower price declines for semiconductors and computers.

The remaining lines of Table 4 show the major factors that contribute to steady-state growth in labor productivity. These numbers highlight the important role of IT in future labor productivity growth. In particular, a comparison of lines 2 and 3 indicates that the induced capital deepening in the steady state is very heavily skewed toward IT capital in both the lower- and upper-bound scenarios, just as it was in the latter half of the 1990s. More broadly, as shown in line 7, the combined contribution of both the induced use and the production of IT accounts for about three-fourths of overall labor productivity growth in both the lower- and upper-bound scenarios.

As indicated above, our intent is to provide a likely range for steady-state growth in labor productivity, not to bound all possible outcomes. For example, the steady-state model can generate labor productivity growth above 3 percent per year if we assume that semiconductor and computer prices continue to fall at the 1996–2001 pace and allow the semiconductor output share to rise by the amount seen between the first and second halves of the 1990s. Conversely, we can generate numbers for labor productivity growth between 1 1/2 and 1 3/4 percent per year if we assume that price declines for computers and semiconductors revert to their historical average and that the computer and semiconductor output shares go back down to levels seen in the first half of the 1990s. So, while we are comfortable with a likely range for steady-state labor productivity growth from 2 percent to 2 3/4 percent, we are well aware of the uncertainty that attends the exercise we have undertaken.

Comparison to other research. Table 5 compares the steady-state results in this paper to those obtained by other researchers. There are two points to take away from this table. First, the range of estimates is very wide, extending from about 1 1/4 percent up to 3 1/4 percent. This range highlights the uncer-

TABLE 5

Alternative Estimates of Steady-State Growth in Labor Productivity, Percent per Year

	Point estimate	Range
1. This paper		2.0 to 2.8
2. Jorgenson, Ho, and Stiroh (2002)[1]	2.25	1.3 to 3.0
3. Congressional Budget Office (2002)[2]	2.2	
4. *Economic Report of the President* (2002)[3]	2.1	
5. Baily (2002)		2.2 to 2.7
6. Gordon[4]		2.0 to 2.2
7. Kiley (2001)		2.6 to 3.2
8. Martin[5]	2.2	1.5 to 2.4
9. McKinsey (2001)[6]	≈2.0	1.6 to 2.5
10. Roberts[7]	2.6	
11. DeLong (2002)	"like the fast-growing late 1990s"	

[1] Jorgenson, Ho, and Stiroh measure productivity growth for a broader definition of the economy than do the other papers. To make their numbers comparable to those in the other studies, add 0.15 percentage point to the point estimate and range shown for Jorgenson, Ho, and Stiroh in the table.
[2] Table 2–5.
[3] Table 1–2, p. 55.
[4] Based on personal correspondence with Robert Gordon, March 24, 2002.
[5] In personal correspondence of August 2002, Bill Martin reported these numbers for the period 2002–11; these figures are lower than those in Martin (2001).
[6] Chapter 3, exhibit 13.
[7] Unpublished update to Roberts (2001).

tainty surrounding the future path of productivity growth. Second, despite the wide band of uncertainty, most of the point estimates (or range midpoints) fall within our range of 2 to 2¾ percent per year. Thus, there is considerable agreement among researchers that productivity growth likely will remain fairly strong going forward.

Conclusion

Recent debates about the pickup of productivity growth in the United States have revolved around two questions. First, are the results from earlier research that emphasized the role of information technology still valid given the sharp contraction in the technology sector? Second, how much of the improvement in labor productivity growth since the mid-1990s could plausibly be sustained? This paper addressed both questions.

As for the robustness of earlier results, we used data through 2001 to reassess the role of information technology in the productivity revival since the mid-1990s. These new growth-accounting results indicate that the story told in Oliner and Sichel (2000a) still stands. Namely, output per hour accelerated substantially after 1995, driven in large part by greater use of IT capital goods by businesses throughout the economy and by more rapid efficiency gains in the production of IT goods.

To address the question of sustainability, we analyzed the steady-state properties of a multisector growth model. This framework translates alternative views about the evolution of the technology sector and other features of the economy into estimates of labor productivity growth in the steady state. When we imposed relatively conservative values for key parameters, this framework generated steady-state growth in labor productivity of about 2 percent per year. This estimate rose to roughly 2¾ percent when we imposed somewhat more optimistic assumptions. We refer to these estimates as structured guesses and think of them as identifying a likely range of productivity outcomes over roughly the next decade. Of course, any such exercise entails substantial uncertainty, and we also discussed scenarios that would generate a wider range of outcomes.

Our analysis highlights that future increases in output per hour will depend importantly on the pace of technological advance in the semiconductor industry and on the extent to which products embodying these advances diffuse through the economy. This observation is consistent with the emphasis in Jorgenson (2001) on semiconductor technology. Gaining a deeper understanding of technological developments in this sector should be a high priority for those attempting to shed light on trends in productivity.

APPENDIX 1

Model of Sectoral Productivity

This appendix presents our model of sectoral productivity and derives key results for our analysis of growth in aggregate labor productivity. The model divides nonfarm business into five sectors. Four of the sectors produce final output (computer hardware, software, communication equipment, and all other final output). The fifth sector produces semiconductors, which are either consumed as an intermediate input by the final-output sectors or exported to foreign firms. To focus on essential linkages, the model abstracts from all intermediate inputs besides semiconductors.

The Model

Let Y_i ($i = 1,\ldots, 4$) denote the production of the final-output sectors. Each sector produces investment goods (I_i) and consumption goods (C_i) for domestic use, where I_i and C_i are identical goods sold to different agents (firms buy I_i, while households buy C_i). Let $I_{i,j}$ and $I_{i,s}$ denote, respectively, the purchases of I_i by final-output sector j (j = 1,…, 4) and by semiconductor producers, with $I_i = \Sigma_j I_{i,j} + I_{i,s}$. Each sector also produces goods for export (X_i). To produce this output, sector i employs labor (L_i) and various types of capital ($K_{j,i}$, j = 1,…, 4), and it purchases semiconductors (S_i) as an intermediate input.[1] With this notation, the production function for each final-output sector can be written as

$$\text{(A1)}\quad Y_i = C_i + \sum_{i=1}^{4} I_{i,j} + I_{i,s} + X_i$$
$$= F_i\,(L_i, K_{1,i}, K_{2,i}, K_{3,i}, K_{4,i}, S_i, z_i)$$
$$\text{for } i = 1,\ldots, 4,$$

where z_i measures the level of multifactor productivity. Although we do not explicitly model foreign production, the capital stocks $K_{j,i}$ should be regarded as including imported capital goods of type j. To ease the notational burden, we have suppressed time subscripts in equation A1 and will do so throughout this appendix.

The output of the semiconductor sector (Y_s) is either sold as intermediate input to the domestic final-output sectors (S_d) or is exported (S_x). The semiconductors purchased by each domestic final-demand sector (S_i) include imported semiconductors (S_m), implying that the production sold for domestic use can be written as $S_d = \Sigma_i S_i - S_m$. We assume that semiconductor producers employ labor and the same set of capital inputs as the final-output sectors. With these assumptions,

$$\text{(A2)}\quad Y_s = S_d + S_x = \sum_{i=1}^{4} S_i + S_x - S_m$$
$$= F_s\,(L_s, K_{1,s}, K_{2,s}, K_{3,s}, K_{4,s}, z_s).$$

The next step is to define the relationship between the sectoral variables and their aggregate counterparts. Following the guidance of index number theory, we express the growth in aggregate final output as a superlative index of growth in sectoral final output. Let $\dot{Z} \equiv (\partial Z/\partial t)/Z$ denote the growth in any variable Z. Then the growth of aggregate nonfarm business output (Y) in our model is

$$\text{(A3)}\quad \dot{Y} = \sum_{i=1}^{4} \mu_i \dot{Y}_i + \mu_{S,x} \dot{S}_x - \mu_{S,m} \dot{S}_m,$$

where $\mu_i \equiv p_i Y_i / pY$ (for i = 1,…, 4), $\mu_{S,x} \equiv p_s S_x / pY$, $\mu_{S,m} \equiv p_s S_m / pY$, and $pY \equiv \Sigma_{i=1}^{4} p_i Y_i + p_s S_x - p_s S_m$.[2] The prices of final output and semiconductors are denoted by p_i and p_s, respectively, and pY represents aggregate current-dollar output. Equation A3 expresses the growth in aggregate output as a share-weighted average of sectoral output growth, where the shares are in current dollars. Note that the semiconductors sold to domestic final-output sectors are an intermediate input for those sectors and thus do not appear in equation A3; only net exports of semiconductors enter the equation, consistent with the treatment of semiconductors in the NIPAs.

The definition of labor and capital aggregates in our model is very simple. We assume that labor input used in a given sector is identical to that used in any other sector. We also impose this assumption on each type of capital. Given these assumptions, we can directly aggregate the sectoral inputs without the need for superlative aggregation formulas. That is,

$$\text{(A4)}\quad L = \sum_{i=1}^{4} L_i + L_s;$$

$$\text{(A5)}\quad K_j = \sum_{i=1}^{4} K_{j,i} + K_{j,s} \text{ for } j = 1,\ldots, 4.$$

Moreover, with this setup, there is a common wage rate (w) for labor in every sector and, likewise, a common rental rate (r_j) for all capital of type j.

Labor input in each sector is the product of hours worked (H_i) and labor quality (q_i), where quality reflects the characteristics of the workers employed in that sector. We allow labor quality to change over time, but given our assumption of identical labor input across sectors, q_i must equal a common value q in every sector at a given point in time. Using equation A4, this implies that

$$\text{(A6)}\quad L = \sum_{i=1}^{4} qH_i + qH_s = qH,$$

where H represents aggregate hours worked.

To derive the growth-accounting equation for each sector, we impose the standard neoclassical assumptions of perfect competition and constant returns to scale. We also assume that there are no adjustment costs. Under these assumptions, profit-maximizing firms will set the marginal revenue product of each input equal to its one-period cost:

$$\text{(A7)}\quad w = p_s(\partial F_s/\partial L_s) = p_i(\partial F_i/\partial L_i) \text{ for } i = 1,\ldots, 4;$$

$$\text{(A8)}\quad r_j = p_s(\partial F_s/\partial K_{j,s}) = p_i(\partial F_i/\partial K_{j,i}) \text{ for } i, j = 1,\ldots, 4;$$

$$\text{(A9)}\quad p_s = p_i(\partial F_i/\partial S_i) \text{ for } i = 1,\ldots, 4.$$

If we totally differentiate equations A1 and A2 and then impose conditions A7 through A9, we obtain the standard growth-accounting equations:

$$\text{(A10)}\quad \dot{Y}_i = \beta_i^L \dot{L}_i + \sum_{j=1}^{4} \beta_{j,i}^K \dot{K}_{j,i} + \beta_i^S \dot{S}_i + \dot{MFP}_i \quad \text{for } i = 1,\ldots, 4;$$

$$\text{(A11)}\quad \dot{Y}_S = \gamma^L \dot{L}_S + \sum_{j=1}^{4} \gamma_j^K \dot{K}_{j,S} + \dot{MFP}_S,$$

where $\dot{MFP}_i \equiv (\partial F_i/\partial z_i)/F_i$, $\dot{MFP}_S \equiv (\partial F_s/\partial z_s)/F_s$, and the βs and γs represent the following income shares: $\beta_i^L \equiv wL_i/p_iY_i$, the labor share in sector i; $\beta_{j,i}^K \equiv r_jK_{j,i}/p_iY_i$, the share for capital of type j in sector i; $\beta_i^S \equiv p_sS_i/p_iY_i$, the semiconductor share in sector i; $\gamma^L \equiv wL_s/p_sY_s$, the labor share in the semiconductor sector; and $\gamma_j^K \equiv r_jK_{j,s}/p_sY_s$, the share for capital of type j in the semiconductor sector. Given the assumption of constant returns, the income shares in each sector sum to one.

Aggregate Labor Productivity

Proposition 1 derives the expression for growth in aggregate labor productivity in our model.

Proposition 1. Assume that all markets are perfectly competitive, that production exhibits constant returns to scale in every sector, and that input use is not subject to adjustment costs. Then, in the model described by equations A1 through A11, the growth-accounting equation for aggregate labor productivity is

$$\dot{Y} - \dot{H} = \sum_{j=1}^{4} \alpha_j^K (\dot{K}_j - \dot{H}) + \alpha^L \dot{q} + \dot{MFP},$$

where $\dot{MFP} = \Sigma_{i=1}^{4} \mu_i \dot{MFP}_i + \mu_s \dot{MFP}_s$, $\alpha^L = wL/pY$, $\alpha_j^K = r_jK_j/pY$, $\mu_i = p_iY_i/pY$, and $\mu_S = p_sY_s/pY$.

Proof. To begin, substitute the expression for $\dot{Y}_i$ from equation A10 into equation A3:

$$\text{(A12)}\quad \dot{Y} = \sum_{i=1}^{4} \mu_i [\beta_i^L \dot{L}_i + \sum_{j=1}^{4} \beta_{j,i}^K \dot{K}_{j,i} + \beta_i^S \dot{S}_i + \dot{MFP}_i] + \mu_{S,x}\dot{S}_x - \mu_{S,m}\dot{S}_m$$
$$= \sum_{i=1}^{4} \alpha^L (L_i/L)\dot{L}_i + \sum_{j=1}^{4}\sum_{i=1}^{4} \alpha_j^K (K_{j,i}/K_j)\dot{K}_{j,i} + \sum_{i=1}^{4} \mu_S (S_i/Y_S)\dot{S}_i + \sum_{i=1}^{4} \mu_i \dot{MFP}_i + \mu_{S,x}\dot{S}_x - \mu_{S,m}\dot{S}_m,$$

where the second equality follows (after some algebra) from the definitions of the αs, βs, and μs. Next, totally differentiate equation A2 to obtain

$$\text{(A13)}\quad \dot{Y}_S = \sum_{i=1}^{4} (S_i/Y_S)\dot{S}_i + (S_x/Y_S)\dot{S}_x - (S_m/Y_S)\dot{S}_m.$$

Multiplying equation A13 by μ_S and using the definitions of μ_S, $\mu_{S,x}$, and $\mu_{S,m}$,

$$\text{(A14)}\quad \sum_{i=1}^{4} \mu_S (S_i/Y_S)\dot{S}_i = \mu_S \dot{Y}_S - \mu_{S,x}\dot{S}_x + \mu_{S,m}\dot{S}_m.$$

Now, substitute equation A14 into equation A12, which yields

$$\text{(A15)}\quad \dot{Y} = \alpha^L \sum_{i=1}^{4} (L_i/L)\dot{L}_i + \sum_{j=1}^{4} \alpha_j^K \sum_{i=1}^{4} (K_{j,i}/K_j)\dot{K}_{j,i} + \sum_{i=1}^{4} \mu_i \dot{MFP}_i + \mu_S \dot{Y}_S.$$

Next, totally differentiate equations A4 and A5:

$$\text{(A16)}\quad \dot{L} = \sum_{i=1}^{4} (L_i/L)\dot{L}_i + (L_S/L)\dot{L}_S;$$

$$\text{(A17)}\quad \dot{K}_j = \sum_{i=1}^{4} (K_{j,i}/K_j)\dot{K}_{j,i} + (K_{j,S}/K_j)\dot{K}_{j,S},$$

and substitute these equations into A15:

1. When either I or K has a double subscript, the first subscript indicates the sector that produced the investment good while the second subscript indicates the sector that uses it as an input to production.
2. Equation A3 is just one of several possible superlative indexes of output growth. It differs slightly from the Fisher chain index used in the NIPAs.

$$\text{(A18)}\quad \dot{Y}=\alpha^L[\dot{L}-(L_S/L)\dot{L}_S]+\sum_{j=1}^{4}\alpha_j^K[\dot{K}_j-(K_{j,S}/K_j)\dot{K}_{j,S}]+\sum_{i=1}^{4}\mu_i\,\dot{MFP}_i+\mu_S\dot{Y}_S$$
$$=\alpha^L\dot{L}+\sum_{j=1}^{4}\alpha_j^K\dot{K}_j+\sum_{i=1}^{4}\mu_i\,\dot{MFP}_i+\mu_S[\dot{Y}_S-(\alpha^L/\mu_S)(L_S/L)\dot{L}_S-\sum_{j=1}^{4}(\alpha_j^K/\mu_S)(K_{j,S}/K_j)\dot{K}_{j,S}]$$
$$=\alpha^L\dot{L}+\sum_{j=1}^{4}\alpha_j^K\dot{K}_j+\sum_{i=1}^{4}\mu_i\,\dot{MFP}_i+\mu_S[\dot{Y}_S-\gamma^L\dot{L}_S-\sum_{j=1}^{4}\gamma_j^K\dot{K}_{j,S}]$$
$$=\alpha^L\dot{L}+\sum_{j=1}^{4}\alpha_j^K\dot{K}_j+\sum_{i=1}^{4}\mu_i\,\dot{MFP}_i+\mu_S\,\dot{MFP}_S,$$

where the third equality follows from the definitions of the αs, γs, and μs, and the fourth equality follows from equation A11. To complete the proof, recall that $\dot{L}=\dot{H}+\dot{q}$ from equation A6 and that the αs sum to one under constant returns to scale. Hence,

$$\text{(A19)}\quad \alpha^L\dot{L}=\alpha^L(\dot{H}+\dot{q})=\dot{H}-\sum_{j=1}^{4}\alpha_j^K\dot{H}+\alpha^L\dot{q}.$$

Substitute equation A19 into A18, which produces

$$\text{(A20)}\quad \dot{Y}-\dot{H}=\sum_{j=1}^{4}\alpha_j^K(\dot{K}_j-\dot{H})+\alpha^L\dot{q}+\sum_{i=1}^{4}\mu_i\dot{MFP}_i+\mu_S\dot{MFP}_S.$$

More on Aggregate MFP

Proposition 1 showed that aggregate MFP growth in our model equals a share-weighted sum of MFP growth in each sector. This result can be rewritten to highlight the input-output connections between semiconductor producers and the final-output sectors. In effect, we can integrate semiconductor producers with the final-output sectors that they supply.

Proposition 2. Under the assumptions of Proposition 1,

$$\dot{MFP}=\sum_{i=1}^{4}\mu_i\,\dot{MFP}_i+\mu_S\,\dot{MFP}_S=\sum_{i=1}^{4}\mu_i[\dot{MFP}_i+\beta_i^S(1+\theta)\dot{MFP}_S],$$

where $1+\theta=Y_S/\Sigma_{i=1}^4 S_i$, the ratio of domestic semiconductor output to domestic use of semiconductors.

Proof. Using equation A2 and recalling the definitions of μ_i, β_i^S, $\mu_{S,x}$, and $\mu_{S,m}$,

$$\text{(A21)}\quad \mu_S\equiv p_SY_S/pY=p_S[\sum_{i=1}^{4}S_i+S_x-S_m]/pY=\sum_{i=1}^{4}(p_iY_i/pY)(p_SS_i/p_iY_i)+p_S(S_x-S_m)/pY=\sum_{i=1}^{4}\mu_i\beta_i^S+\mu_{S,x}-\mu_{S,m}.$$

Note that $\mu_{S,x}-\mu_{S,m}$ can be written as $\mu_S(S_x-S_m)/Y_S$ so that equation A21 becomes

$$\text{(A22)}\quad \mu_S=\sum_{i=1}^{4}\mu_i\beta_i^S/[1-(S_x-S_m)/Y_S]=\sum_{i=1}^{4}\mu_i\beta_i^S/[\sum_{i=1}^{4}S_i/Y_S]=\sum_{i=1}^{4}\mu_i\beta_i^S(1+\theta),$$

where the second equality follows from equation A2 and the third from the definition $1+\theta\equiv Y_S/\Sigma_{i=1}^4 S_i$. Finally, substitute equation A22 into the expression from Proposition 1 for growth in aggregate *MFP*:

$$\text{(A23)}\quad \dot{MFP}=\sum_{i=1}^{4}\mu_i\,\dot{MFP}_i+\mu_S\,\dot{MFP}_S=\sum_{i=1}^{4}\mu_i[\dot{MFP}_i+\beta_i^S(1+\theta)\dot{MFP}_S].$$

Measuring Sectoral MFP

To make use of Propositions 1 and 2, we need to estimate MFP growth in each sector. This estimate can be derived either from the sectoral production functions, as in equations A10 and A11, or from the sectoral cost functions—the "dual" approach. We opt for the dual approach because the required data are more readily available. The dual counterparts to equations A10 and A11 are:

$$\text{(A24)}\quad \dot{p}_i=\beta_i^L\dot{w}+\sum_{j=1}^{4}\beta_{j,i}^K\dot{r}_j+\beta_i^S\dot{p}_S-\dot{MFP}_i\quad \text{for } i=1,\ldots,4;$$

$$\text{(A25)}\quad \dot{p}_S=\gamma^L\dot{w}+\sum_{j=1}^{4}\gamma_j^K\dot{r}_j-\dot{MFP}_S.$$

These equations state that the growth in each sector's output price equals the growth in the share-weighted average of its input costs minus the growth in MFP. MFP growth enters with a negative sign because efficiency gains hold down a sector's output price given its input costs.

To reduce the amount of data needed to estimate MFP growth from equations A24 and A25, we assume that every sector has the same labor and capital shares up to a scaling factor that reflects the intensity of semiconductor use. That is, (A26) $$\frac{\beta_1^L}{1-\beta_1^S}=\ldots=\frac{\beta_4^L}{1-\beta_4^S}=\gamma^L \quad \text{and}$$

$$\frac{\beta_{j,1}^K}{1-\beta_1^S}=\ldots=\frac{\beta_{j,4}^K}{1-\beta_4^S}=\gamma_j^K \quad \text{for } j = 1,\ldots, 4.$$

One can easily verify that the restricted factor shares sum to one in each sector. Also, given equation A26, one can show (with some algebra) that $\gamma^L = \alpha^L$ and $\gamma_j^K = \alpha_j^K$; that is, the income shares for aggregate nonfarm business equal their counterparts in the semiconductor sector. Substituting equation A26 into A24 and making use of the correspondence between the γs and the αs, we obtain

(A27) $$\dot{p}_i = (1-\beta_i^S)[\alpha^L \dot{w}+\sum_{j=1}^{4}\alpha_j^K \dot{r}_j]+\beta_i^S \dot{p}_S-\dot{MFP}_i \quad \text{for } i = 1,\ldots 4.$$

Let $\dot{V} \equiv (\alpha^L \dot{w} + \Sigma_{j=1}^{4} \alpha_j^K \dot{r}_j)$ denote the share-weighted growth in labor and capital costs for the nonfarm business sector as a whole. Substitute $\dot{V}$ into the dual equations A25 and A27, noting that $\gamma^L = \alpha^L$ and $\gamma_j^K = \alpha_j^K$ in equation A25. The result is

(A28) $$\dot{p}_i = (1-\beta_i^S)\dot{V}+\beta_i^S \dot{p}_S - \dot{MFP}_i \quad \text{for } i = 1,\ldots, 3;$$

(A29) $$\dot{p}_4 = (1-\beta_4^S)\dot{V}+\beta_4^S \dot{p}_S - \dot{MFP}_4;$$

(A30) $$\dot{p}_S = \dot{V} - \dot{MFP}_S,$$

where we have specifically identified sector 4, which will serve as the numeraire sector.

We now use the dual equations to derive expressions for MFP growth in two cases. In the first case, we infer the rates of sectoral MFP growth that are consistent with an independent estimate of aggregate MFP growth (from the Bureau of Labor Statistics). This case represents the methodology we use to compute growth contributions through 2001. In the second case, which we use for our steady-state analysis, we solve for aggregate MFP growth and MFP growth in sectors 1 through 3, conditional on an assumed pace of MFP growth in sector 4. The next proposition derives the expressions for sectoral MFP growth in both cases.

Proposition 3. Let $\pi_S \equiv \dot{p}_s - \dot{p}_4$ and $\pi_i \equiv \dot{p}_i - \dot{p}_4$ ($i = 1,\ldots, 3$) denote the rate of change in each sector's output price relative to that in sector 4. Given the dual equations A28–A30, the solutions for sectoral and aggregate MFP growth are as follows.

Case I: Conditioning on Aggregate MFP Growth

$$\dot{MFP}_4 = (1-\beta_4^S)(\dot{MFP}+\sum_{i=1}^{3}\mu_i\pi_i) +[\beta_4^S+(1-\beta_4^S)(1-\sum_{i=1}^{4}\mu_i)]\pi_S$$

$$\dot{MFP}_S = (\dot{MFP}_4 - \pi_S)/(1-\beta_4^S)$$

$$\dot{MFP}_i = \dot{MFP}_4 - \pi_i - (\beta_i^S - \beta_4^S)\dot{MFP}_S \quad \text{for } i = 1,\ldots, 3$$

Case II: Conditioning on MFP Growth in Sector 4

$$\dot{MFP}_S = (\dot{MFP}_4 - \pi_S)/(1-\beta_4^S)$$

$$\dot{MFP}_i = \dot{MFP}_4 - \pi_i - (\beta_i^S - \beta_4^S)\dot{MFP}_S \quad \text{for } i = 1,\ldots, 3$$

$$\dot{MFP} = \sum_{i=1}^{4}\mu_i \dot{MFP}_i + \mu_S \dot{MFP}_S$$

Proof. The proof for Case II is nearly immediate. Subtract equation A29 from equations A28 and A30. After rearranging terms and using equation A30 to substitute $\dot{MFP}_s$ for $\dot{V} - \dot{P}_s$, we obtain

(A31) $$\dot{MFP}_i = \dot{MFP}_4 - \pi_i - (\beta_i^S - \beta_4^S)\dot{MFP}_S \quad \text{for } i = 1,\ldots, 3;$$

(A32) $$\dot{MFP}_S = (\dot{MFP}_4 - \pi_S)/(1-\beta_4^S).$$

Equations A31 and A32, plus the expression for $\dot{MFP}$ derived in Proposition 1, establish the results for Case II. Note that the solution is recursive—first solve for $\dot{MFP}_s$ from equation A32, then substitute the result into equation A31, and finally substitute all the sectoral MFP growth rates into the expression for aggregate MFP growth.

To prove the result for Case I, substitute equations A31 and A32 into the expression for aggregate MFP growth. After rearranging terms, this substitution yields

(A33)

$$\dot{MFP} = \sum_{i=1}^{4}\mu_i \dot{MFP}_i + \mu_S \dot{MFP}_S$$
$$= [\sum_{i=1}^{4}\mu_i + [\mu_S - \sum_{i=1}^{3}\mu_i(\beta_i^S - \beta_4^S)]/(1-\beta_4^S)]\dot{MFP}_4$$
$$-\sum_{i=1}^{3}\mu_i\pi_i - [[\mu_S - \sum_{i=1}^{3}\mu_i(\beta_i^S - \beta_4^S)]/(1-\beta_4^S)]\pi_S.$$

Let $B \equiv \Sigma_{i=1}^{4}\mu_i + [\mu_S - \Sigma_{i=1}^{3}\mu_i(\beta_i^S - \beta_4^S)]/(1-\beta_4^S)$ and solve equation A33 for $\dot{MFP}_4$:

$$\text{(A34)}\quad \dot{MFP}_4 = (\dot{MFP} + \sum_{i=1}^{3}\mu_i\pi_i)/B + \pi_S(B - \sum_{i=1}^{4}\mu_i)/B.$$

With tedious algebra, one can show that B simplifies to be $1/(1 - \beta_4^S)$. Using this expression for B, equation A34 becomes

$$\text{(A35)}\quad \dot{MFP}_4 = (1-\beta_4^S)(\dot{MFP} + \sum_{i=1}^{3}\mu_i\pi_i) + [\beta_4^S + (1-\beta_4^S)(1 - \sum_{i=1}^{4}\mu_i)]\pi_S.$$

This equation, combined with equations A31 and A32, completes the proof for Case I. As in Case II, the solution is recursive. First, solve for $\dot{MFP}_4$ from equation A35. Then, substitute the result into equations A31 and A32.

Analysis of the Steady State

The results presented so far do not require the economy to have reached a steady state. We now impose additional conditions to derive the growth-accounting equation for aggregate labor productivity in the steady state.

The first steady-state condition is that labor input must grow at the same rate in every sector:

$$\text{(A36)}\quad \dot{L} = \dot{L}_S = \dot{L}_i \text{ for } i = 1,\dots, 4.$$

We also require that all components of a given sector's output grow at the same rate. Referring back to equations A1 and A2, this condition implies the following for the final-output sectors and the semiconductor sector, respectively:

$$\text{(A37)}\quad \dot{Y}_j = \dot{C}_j = \dot{X}_j = \dot{I}_{j,s} = \dot{I}_{j,i} \text{ for } i, j = 1,\dots, 4$$

$$\text{(A38)}\quad \dot{Y}_S = \dot{S}_x = \dot{S}_m = \dot{S}_i \text{ for } i = 1,\dots, 4.$$

In addition, we require that all the growth rates in equations A36–A38 be constant and that the imported share of each sector's capital stocks be constant as well. Because $I_{j,i}$ grows at a constant rate over time, the stock of this (domestically produced) capital will grow at the same constant rate. Moreover, with the imported share of each capital stock assumed to be constant, the total stock, including imported capital, $K_{j,i}$, will grow at the same rate as the domestically produced part.

This reasoning implies that $\dot{I}_{j,i} = \dot{K}_{j,i}$ and $\dot{I}_{j,s} = \dot{K}_{j,s}$ for all i and j. Combining these equalities with equation A37, we obtain

$$\text{(A39)}\quad \dot{Y}_j = \dot{K}_{j,i} = \dot{K}_{j,s} \text{ for } i, j = 1,\dots, 4.$$

Proposition 4. Under the steady-state conditions in equations A36–A39 and the restrictions on the income shares across sectors (equation A26), the growth-accounting equation for aggregate labor productivity is

$$\dot{Y} - \dot{H} = \sum_{i=1}^{4}(\alpha_i^K/\alpha^L)(\dot{MFP}_i + \beta_i^S\dot{MFP}_S) + \dot{q} + \dot{MFP},$$

where

$$\dot{MFP} = \sum_{i=1}^{4}\mu_i\dot{MFP}_i + \mu_S\dot{MFP}_S.$$

Proof. Substitute equations A26, A36, A38, and A39 into the growth-accounting equations A10 and A11, and recall that $\gamma^L = \alpha^L$ and $\gamma_j^K = \alpha_j^K$ when we impose the cross-sector restrictions on the income shares. The result is

$$\text{(A40)}\quad \dot{Y}_i = (1-\beta_i^S)\alpha^L\dot{L} + \sum_{j=1}^{4}(1-\beta_i^S)\alpha_j^K\dot{Y}_j + \beta_i^S\dot{Y}_S + \dot{MFP}_i \text{ for } i = 1,\dots, 4$$

$$\text{(A41)}\quad \dot{Y}_S = \alpha^L\dot{L} + \sum_{j=1}^{4}\alpha_j^K\dot{Y}_j + \dot{MFP}_S.$$

Equations A40 and A41 form a system of five equations in $(\dot{Y}_1,\dots, \dot{Y}_4, \dot{Y}_S)$. Solving this system yields

$$\text{(A42)}\quad \dot{Y}_i = \dot{L} + \dot{MFP}_i + \sum_{j=1}^{4}(\alpha_i^K/\alpha^L)\dot{MFP}_j + [\beta_i^S + \sum_{j=1}^{4}(\alpha_i^K/\alpha^L)\beta_j^S]\dot{MFP}_S$$

for $i = 1,\dots, 4$;

$$\text{(A43)}\quad \dot{Y}_S = \dot{L} + \sum_{j=1}^{4}(\alpha_i^K/\alpha^L)\dot{MFP}_j + [1 + \sum_{j=1}^{4}(\alpha_i^K/\alpha^L)\beta_j^S]\dot{MFP}_S.$$

Now, substitute equations A42 and A43 into equation A3 (the expression for growth in aggregate output) and rearrange terms, noting that $\dot{S}_x = \dot{S}_m = \dot{Y}_s$ from equation A38:

(A44) $$\dot{Y} = \sum_{i=1}^{4} \mu_i \dot{Y}_i + \mu_{S,x} \dot{S}_x - \mu_{S,m} \dot{S}_m$$
$$= \sum_{i=1}^{4} \mu_i \dot{Y}_i + (\mu_{S,x} - \mu_{S,m}) \dot{Y}_S$$
$$= \dot{L} + \sum_{i=1}^{4} (\alpha_i^K / \alpha^L)(\dot{MFP}_i + \beta_i^S \dot{MFP}_S)$$
$$+ \sum_{i=1}^{4} \mu_i \dot{MFP}_i + [\sum_{i=1}^{4} \mu_i \beta_i^S + \mu_{S,x} - \mu_{S,m}] \dot{MFP}_S.$$

Recalling that $\dot{L} = \dot{H} + \dot{q}$ and that $\mu_S = \Sigma_{i=1}^{4} \mu_i \beta_i^S + \mu_{S,x} - \mu_{S,m}$ from equation A21, we obtain

(A45) $$\dot{Y} - \dot{H} = \sum_{i=1}^{4} (\alpha_i^K / \alpha^L)(\dot{MFP}_i + \beta_i^S \dot{MFP}_S)$$
$$+ \dot{q} + \sum_{i=1}^{4} \mu_i \dot{MFP}_i + \mu_S \dot{MFP}_S.$$

APPENDIX 2

Data Sources

This appendix describes the data series used in the paper. All data are annual and cover the period from 1973 to 2001. Note that we have not incorporated the July 2002 revision of the NIPAs, which was released while the paper was in production.

Real Output in the Nonfarm Business Sector (*Y*)

Data through 2000 are from the BLS multifactor productivity data set. (The version we used was released in March 2002.) In constructing output, the BLS relies primarily on the BEA real output series for nonfarm business less housing. Both the BEA and BLS series are superlative indexes of output. For 2001, we extended the BLS series using annual growth rates of the BEA series for real output in nonfarm business less housing (NIPA, table 1.8).

Both the BLS and the BEA have incorporated the effects of technical changes to the consumer price index (CPI) back to 1978 (specifically, the introduction of geometric means in the CPI). However, the output data prior to 1978 must be adjusted to be methodologically consistent with the later data. According to the *Economic Report of the President* (1999, 94), the introduction of geometric means prior to 1978 would hold down CPI inflation by 0.2 percentage point per year. From 1973 to 1977, consumption expenditures accounted for about 85 percent of nonfarm business output in current dollars. Thus, the incorporation of geometric means prior to 1978 would reduce inflation in nonfarm business prices by about 0.17 percentage point per year (0.2 × 0.85) through 1977 and would boost growth in nonfarm business output by the same amount each year. In 1978, the adjustment is smaller because the growth rate for that year, which depends on the level in 1977 and the level in 1978, straddles the change in methodology. To account for these effects, we added 0.17 percentage point to the growth rate of the BLS series for nonfarm business output for each year through 1977 and 0.09 percentage point in 1978.

Price Index for Nonfarm Business Output (*p*)

We measured *p* as an implicit price deflator, constructed as the ratio of current-dollar nonfarm business output to real nonfarm business output from the BLS multifactor productivity data set. To build in the effects of the CPI revision described in the previous paragraph, we then adjusted down the rate of change of this BLS series by 0.17 percentage point annually for 1974–77 and by 0.09 percentage point for 1978. For the rate of change in 2001, we extended the BLS series using the annual growth rate of BEA's price index for nonfarm business less housing.

Capital Inputs (K_C, K_{SW}, K_M, K_O)

We constructed these capital inputs in two steps. The first step develops productive capital stocks for a detailed set of assets. The second step aggregates these detailed stocks to the four capital inputs used in our analysis.

Productive stocks for detailed types of capital. For each type of capital, we took data through 2000 directly from the BLS multifactor productivity data set. The BLS constructs productive stocks for highly disaggregated asset categories, starting with data on real investment for sixty-one different types of business capital and then translating these investment flows into productive stocks with the use of hyperbolic age-efficiency profiles.

We extended these BLS productive stocks to 2001 as follows.[1] For nonresidential fixed capital—which constitutes a large majority of all capital used in nonfarm business—we extended the detailed BLS investment series to 2001 using NIPA investment data for five broad asset groups: computers and peripheral equipment, software, communication equipment, other equipment, and nonresidential structures. For each group except computers and peripheral equipment, we used the growth rate of investment in 2001 for the group as a whole to extend the investment series for each asset within the group. For example, we used the 2001 growth rate for overall NIPA software investment to extend the investment series for each of the three different types of software.

For computers and peripheral equipment, we employed a more refined procedure to capture the differences in trend growth rates across the assets in this important group. To begin, we used the BLS data set to calculate the average growth rate of investment in 1999 and 2000 for each type of computer and peripheral equipment—mainframes, personal computers, printers, terminals, integrated systems, and three different types of storage devices. These growth rates represented our estimate of "trend" growth in investment for 2001 for each detailed category. Then we scaled these trend rates so that the resulting individual investment series would chain aggregate to the level of total real investment in computers and peripheral equipment in 2001.[2]

Given an estimate of real investment in 2001 for each type of nonresidential fixed capital, we extended the BLS productive capital stocks to 2001 with the perpetual inventory method. Specifically, for each detailed asset type, we calculated a translation factor (f_t) for each year through 2000 from the following equation:

$$K_t = f_t K_{t-1} + (I_t + I_{t-1})/2,$$

where (following BLS methodology) K_t is measured as the average of the stocks at the end of years t and $t - 1$. We used the value of f_t in 2000 and the detailed investment data to construct productive stocks for each type of nonresidential fixed capital for 2001.

The other assets included in the BLS measure of nonfarm business capital are tenant-occupied rental housing, inventories, and land. For tenant-occupied rental housing, we extended the BLS productive stock to 2001 with a simple regression equation. This equation regressed the BLS productive stock on its own lag and on real investment in multifamily residential structures from the NIPAs. The coefficients from this equation, combined with NIPA data on investment in multifamily structures for 2001, generated the estimate of the stock of tenant-occupied rental housing in 2001. For the stock of inventories, we extended the BLS series to 2001 using NIPA inventory data. For the stock of land, we extended the BLS series to 2001 with the average growth rate of this stock for the five years through 2000.

Aggregation. The BLS uses the Tornquist formula to aggregate the detailed productive capital stocks into measures of capital services. The Tornquist aggregate is a weighted average of the growth rates of the various productive stocks, with the weight for each asset type equal to its estimated share of total capital income. To construct our capital aggregate for computer and peripheral equipment (K_C), we applied the Tornquist formula to the eight components of such equipment. For software (K_{SW}), we followed a similar procedure for the three different types of software. For communication equipment (K_M), the capital services aggregate just equals the productive stock; the Tornquist formula is not needed because we have no asset detail within this aggregate. Finally, to construct K_O, our first step was to extend the BLS measure of aggregate capital services to 2001 (using the Tornquist formula). Then, we stripped out computer and peripheral equipment, software, and communication equipment from aggregate capital services to arrive at K_O.

Labor Hours (*H*)

Through 2000, labor hours are from the BLS multifactor productivity data set. We extended the data to 2001 using the growth rate in hours of all persons in the nonfarm business sector from the BLS Productivity and Cost release.

Labor Quality (*q*)

The BLS measures labor quality as the difference in the growth rate of labor input and labor hours. To calculate labor input, the BLS divides the labor force into a number of age-sex-education cells and then constructs a weighted average of growth in hours worked in each cell, with the weight for each cell equal to its share of total labor compensation. Through 2000, our measure of labor quality is from the BLS multifactor productivity data set. For 2001, we assumed that labor quality generated a contribution of 0.25 percentage point to growth in labor productivity, its average contribution over 1996–2000.

Income Shares (α_j)

The income share for each detailed type of nonresidential fixed capital in a given year was calculated from the following equation:

$$\alpha_j = (R + \delta_j - \Pi_j)p_j K_j T_j / pY.$$

We discuss each component of this equation below. Note that these income shares vary from year to year and are not fixed at a period-average value.

For tenant-occupied rental housing, inventories, and land, the income shares through 2000 were taken directly from the BLS multifactor productivity data set. For 2001, we extrapolated forward the BLS year-2000 level of capital income for each asset using the trend growth rate from 1995 to 2000. We then divided the estimated 2001 capital income for each asset by total income in nonfarm business to obtain income shares.

Once we estimated the income-share series for each capital asset, the income share for labor equaled unity minus the total income share for capital.

Depreciation rate (δ_j). For the most part, the depreciation rate for each type of equipment and structure comes from the BEA (as presented in Fraumeni 1997, 18–19). However, as indicated above, the BEA provides very little information on depreciation rates for the individual types of computers and peripheral equipment; we followed Whelan (2000) and set these depreciation rates equal to a geometric approximation calculated from the BEA capital stocks and investment flows. For personal computers, we are uncomfortable with the BEA's procedure for depreciation rates, and instead we set the depreciation rate for PCs equal to the 30 percent annual rate for mainframe computers.[3] For software, we used the BEA depreciation rates described by Herman (2000, 19). The BEA assumes that prepackaged software has a service life of three years and a depreciation rate of 55 percent per year; own-account and custom software each have service lives of five years and a depreciation rate of 33 percent per year.

Expected nominal capital gain/loss (Π_j). We calculated Π_j as a three-year moving average of the percent change in the price of asset j (p_j). The moving average serves as a proxy for the unobserved expectation of price change. Through 2000, the p_j series for each asset is the investment price index from the BLS multifactor productivity data set. Each p_j series was extended to 2001 using the same procedure as that employed for real investment for each asset. Specifically, we extended the detailed BLS price series to 2001

1. The BLS actually relies on a two-way disaggregation by type of asset and by industry. For our analysis, we used data by asset that already have been aggregated across industries.
2. This scaling procedure does not generate sensible results if the estimated trend growth rate of investment for a particular asset differs in sign from the actual 2001 change for the broader group to which it belongs. Because such sign differences periodically occur for some assets within software, communication equipment, other equipment, and nonresidential structures, we used the simpler procedure described above for extending investment in business fixed assets other than computer hardware.
3. As described in Herman (2000, 20), the BEA sets the depreciation rate for personal computers so that 10 percent of the original value remains after five years of service, which implies an annual geometric depreciation rate of 37 percent. By construction, this depreciation rate captures the full loss of value during each year of the assumed five-year service life. In contrast, the BEA's depreciation rates for other types of computer hardware are constructed to capture only the loss of value over and above the decline in the asset's constant-quality price index (Π_j). This concept of depreciation is the appropriate one to combine with Π_j in order to measure the full loss of asset value in the formula for the income share. However, for personal computers, the BEA's depreciation rate, when combined with Π_j, double-counts the loss of value. One fix for this problem would be to drop the Π_j term from the income-share formula for PCs. However, doing so would be appropriate only if the BEA's depreciation rate of 37 percent accurately measures the full loss of value. While there is relatively little hard evidence on this subject, our sense is that PCs typically lose more than 37 percent of their value over the course of a year. Thus, dropping the Π_j term from the user cost formula does not seem an adequate solution to this problem. Instead, we set δ_j for PCs equal to the value for mainframes (30 percent per year) and plugged this value into the income-share formula, along with the value of Π_j for PCs. This may not be an ideal approach, but given the very limited research on depreciation for PCs, we judged it to be the best choice at present. (For a fuller discussion of related issues, see Oliner 1994.) Similar problems may affect other assets as well, and we believe that future research in this area is crucial.

using NIPA investment prices for five broad categories of nonresidential fixed investment: computers and peripheral equipment, software, communication equipment, other equipment, and nonresidential structures.[4] For each individual asset, the resulting rate of price change was applied to the year-2000 level of p_j to calculate p_j for 2001.

Current-dollar productive capital stock (p_jK_j). For each asset, this series is simply the product of the real productive stock (K_j) and the asset price index (p_j), both of which are discussed above.

Tax adjustment (T_j). For each asset, this adjustment equals $(1 - c - \tau v)/(1 - \tau)$, where c is the rate of investment tax credit, τ is the corporate tax rate, and v is the present value of $1 of tax depreciation allowances. Karl Whelan kindly provided these series, which are discussed further in Whelan (1999).

Current-dollar nonfarm business output (pY). Through 2000, this series is from the BLS multifactor productivity data set. For 2001, we extended the BLS series using the annual growth rate of the BEA series for current-dollar output in the nonfarm business sector less housing.

Nominal net return (R). We calculated R as the ex post net return earned on the productive stock of nonresidential equipment and structures. Thus, we obtained R as the solution to the following equation for each year in our sample:

$$\sum_{j=1}^{N}(R + \delta_j - \Pi_j)p_jK_jT_j/pY = \text{BLS series for} \sum_{j=1}^{N}\alpha_j,$$

where the summations are over all N types of nonresidential equipment, software, and structures. This procedure yielded an annual series for R through 2000. For 2001, we estimated R from a regression with the following explanatory variables: a constant, two lags of R, the rate of price change for nonfarm business output, the acceleration in real nonfarm business output, the unemployment rate, and the share of corporate profits in GNP.

Current-Dollar Output Shares ($\mu_C, \mu_{SW}, \mu_M, \mu_S, \mu_O$)

The denominator of each output share is current-dollar nonfarm business output (pY), the data source for which was described above. Here, we focus on the measurement of current-dollar sectoral output, the numerator in each share.

Computer sector. We used NIPA data on final sales of computers to measure current-dollar computer output (p_CY_C). NIPA final sales equals the sum of current-dollar spending on computers and peripheral equipment in the following categories: private fixed investment, personal consumption expenditures, government expenditures, and net exports of goods and services. This sum omits the small portion of final computer output that ends up in business inventories because the NIPA inventory data do not break out computing equipment from other inventories.

Software sector. To estimate $p_{SW}Y_{SW}$, we started with unpublished data from the BEA on current-dollar final sales of software from 1987 to 2000. We then adjusted this series for software not produced in the nonfarm business sector by stripping out the BEA estimate of own-account software produced by the government.[5] Finally, we extended the 1987 level back to earlier years and the 2000 level forward to 2001 using NIPA data on growth in current-dollar software investment by businesses.

Communication equipment sector. To estimate p_MY_M, we used unpublished data from the BEA on total current-dollar final sales of communication equipment from 1997 to 2000. We extended the 1997 level back in time and the 2000 level forward to 2001 using NIPA data on the growth of current-dollar business investment in communication equipment.

Semiconductor sector. Our series for current-dollar semiconductor output (p_SY_S) equals current-dollar shipments of products in SIC category 36741 (integrated microcircuits). Federal Reserve Board staff construct this shipments series as an input to the Board's index of industrial production, using Census Bureau reports through 1999 and trade data from the Semiconductor Industry Association (SIA) for 2000 and 2001. Because the shipments series is not available before 1977, we set the value of the semiconductor output share (μ_S) during 1973–76 equal to its 1977 value.

Other final-output sector. We estimated current-dollar output in this sector (p_OY_O) as a residual after accounting for all other components of nonfarm business output:

$$p_OY_O = pY - p_CY_C - p_{SW}Y_{SW} - p_MY_M - p_S(S_x - S_m),$$

where the final term is current-dollar net exports of semiconductors. (This is the only part of semiconductor production that shows up in domestic final output.) The data sources for pY, p_CY_C, $p_{SW}Y_{SW}$, and p_MY_M were described above. We obtained data on current-dollar net exports of semiconductors as follows. For the period from 1989 to 2001, we started with series constructed by Federal Reserve Board staff for current-dollar exports and imports of products in SIC code 3674 (semiconductors and related devices), which are based on detailed figures from the International Trade Commission. Because the 3674 category is broader than just semiconductors, we scaled the export and import series for SIC code 3674 down to 36741 (integrated microcircuits) using the ratio of domestic shipments in 36741 to domestic shipments in 3674. Prior to 1989, we did not have detailed trade data, and we extended the export and import series back in time using the rate of change in domestic shipments of semiconductors (the series $p_S Y_S$ described above).

Ratio of Semiconductor Output to Domestic Semiconductor Use (1 + θ)

Domestic semiconductor use can be expressed as domestic semiconductor output minus net exports of semiconductors. Thus,

$$1 + \theta = Y_S / [Y_S - (S_x - S_m)]$$
$$= p_S Y_S / [p_S Y_S - (p_S S_x - p_S S_m)],$$

where the second equality converts each series to current dollars. The data sources for $p_S Y_S$ and $p_S S_x - p_S S_m$ were described above.

Rates of Relative Price Change (π_C, π_{SW}, π_M, π_S)

Each π_i series ($i = C, SW, M,$ and S) represents the rate of change in the price ratio p_i / p_O. Here, we describe the data source for each price series that enters these ratios.

Computer sector. p_C is measured as an implicit price deflator for the output of computers in the NIPAs. We calculated this deflator as the ratio of current-dollar computer output (defined as the sum of all final sales of computers and denoted above by $p_C Y_C$) to a chain aggregate of real outlays for the same spending categories, which we denote by Y_C.

Software sector. p_{SW} is an implicit price deflator for software produced in the nonfarm business sector. Using NIPA data, we calculated this deflator as the ratio of current-dollar software output (the series $p_{SW} Y_{SW}$ described above) to a chain aggregate of real software outlays denoted by Y_{SW}. To construct Y_{SW}, we did a "chain strip-out" of government own-account software from total final sales of software, parallel to our calculation of the current-dollar series. The growth rate of the resulting aggregate series for real software outlays was about 1 percentage point per year higher than the growth rate of real business investment in software over 1987–2000, the period over which we can construct Y_{SW}. To extend Y_{SW} back to years before 1987 and forward to 2001, we used the annual growth rates of real business investment in software adjusted by this 1987–2000 wedge.[6]

Communication equipment sector. p_M is an implicit deflator for the output of communication equipment in the NIPAs. We calculated this deflator as the ratio of current-dollar outlays for communication equipment (the series $p_M Y_M$ defined above) to a chain aggregate of real outlays denoted by Y_M and constructed in an analogous manner to $p_M Y_M$. To calculate Y_M we used unpublished data from the BEA on total real final sales of communication equipment from 1997 to 2000. We extended the 1997 level back in time and the 2000 level to 2001 using published NIPA data on the growth of real business investment in communication equipment.

Other final-output sector. Like the other price series, p_O is an implicit deflator, which equals the ratio of current-dollar output for this sector (the series $p_O Y_O$ defined above) to a chain aggregate of the sector's real output (Y_O). We constructed Y_O by starting with our series for real nonfarm business output (Y) and then chain-stripping-out all other components of Y (that is, real output of computers, software, and communication equipment, along with real exports and

4. Just as for the investment series, the scaling procedure that we used for computer hardware does not generate sensible results if the trend rate of price change for a particular asset differs in sign from the actual 2001 change for the broader group to which it belongs. Because these sign differences occur for some noncomputer price series, we employed the simpler extrapolation method described above to extend the price series for nonresidential fixed investment other than computer hardware.
5. Estimates of government own-account software from 1996 to 2000 are available as unpublished data from the BEA. In addition, Parker and Grimm (2000) provide estimates of government own-account software for 1979 and 1992. Using these values, we linearly interpolated the government own-account series backward in time.
6. Real software output is the only extrapolated series for which we used a wedge adjustment. For other extrapolated series, there was not a significant difference between the growth rate of the series in question and the extrapolator series.

imports of semiconductors). Roughly speaking, the chain strip-out inverts equation A3 in Appendix 1 to solve for the growth of Y_O, and the resulting growth rates are then linked together to create a series in index levels. To construct the series for real exports and imports of semiconductors needed for the chain strip-out, we assumed that the price of exports and imports of semiconductors was equal to the semiconductor price series described in the next paragraph.

Semiconductor sector. For 1977–2001, the data source for p_S is the deflator for SIC 36741 that Federal Reserve staff developed to estimate industrial production; we used this series to compute the annual percent change in p_S for 1978 through 2001. For years before 1978, we calculated the percent change in p_S by extrapolating back in time using data from Grimm (1998). Specifically, we calculated the average annual percent change between 1974 and 1977 in Grimm's "Summary price index for MOS memory chips" (p. 12), and then took the ratio of this average 1974–77 percent change to the percent change for 1978 based on the Federal Reserve series. We multipied the 1978 percent change in the Federal Reserve series by this ratio and used the resulting value as the percent change in p_S for each year from 1974 to 1977.

Semiconductors as a Share of Current-Dollar Input Costs (β_C^s, β_{SW}^s, β_M^s, β_O^s)

Computer sector. We set β_C^s equal to 0.3 for all years. That is, we assumed that semiconductors account for 30 percent of the current-dollar input cost of computer producers. This value lies at the middle of the range employed by Triplett (1996). Although the SIA publishes data on semiconductor usage by the computer industry, these data are not appropriate for our purpose. As noted by Flamm (1997, 11), the SIA data cover only the semiconductors sold by "merchant" producers in the open market; these data exclude "captive" production by U.S. computer manufacturers, notably IBM. Thus, the SIA-based measure would greatly understate semiconductor use during the 1970s and 1980s, when IBM was the dominant U.S. computer producer.

Software sector. We set β_{SW}^s to zero because semiconductors are not a direct input to software production. (Of course, the software industry uses computers and communication equipment that contain semiconductors, but it does not directly use semiconductors.)

Communication equipment sector. We used data from the SIA to construct β_M^s. The SIA provides data on worldwide shipments of semiconductors for 1976–2001. The SIA also publishes data for 1985–94 on the share of these worldwide shipments purchased by producers of communication equipment in the United States. After 1994, the SIA redefined this latter series to cover "the Americas." We linked the series on the U.S.-only share through 1994 with the series on the Americas share from 1995 forward. (Because the share figures are available only back to 1985, we set this share for earlier years equal to the 1985 value.) We then multiplied the resulting share series by worldwide semiconductor shipments to calculate the current-dollar value of semiconductors used by the communication equipment industry in the United States. (To the extent that semiconductors are used to produce communication equipment elsewhere in North or South America, the series will overstate semiconductor use in the United States alone from 1995 forward.) To construct β_M^s, we divided the series just described by our estimate of the current-dollar value of communication equipment produced in the United States, $p_M Y_M$. Prior to 1976 (for which data on worldwide semiconductor shipments are not available), we set β_M^s equal to its 1976 value.

Other final-output sector. To estimate β_O^s, recall the expression for μ_S in equation A22 of Appendix 1:

$$\mu_S = \sum_{i=1}^{4} \mu_i \beta_i^S (1+\theta),$$

which can be written with explicit sectoral notation as

$$\mu_S = [\mu_C \beta_C^S + \mu_{SW} \beta_{SW}^S + \mu_M \beta_M^S + \mu_O \beta_O^S](1+\theta).$$

Solving this equation for β_O^S yields

$$\beta_O^S = \frac{\mu_S - (1+\theta)[\mu_C \beta_C^S + \mu_{SW} \beta_{SW}^S + \mu_M \beta_M^S]}{\mu_O (1+\theta)}.$$

The data sources for all series on the right-hand side of this expression have already been discussed.

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Technology and U.S. Wage Inequality: A Brief Look

DAVID CARD AND JOHN E. DINARDO

Card is a professor in the Department of Economics at the University of California, Berkeley. DiNardo is a professor in the Department of Economics and School of Public Policy at the University of Michigan, Ann Arbor. *They thank Ken Chay and David Lee for many helpful discussions, Charles Nelson of the U.S. Census Bureau and Anne Polivka of the Bureau of Labor Statistics for assistance in using the data, and Elizabeth Cascio for outstanding research assistance. They also thank David Autor, Daniel Hamermesh, Lawrence Katz, Paul Beaudry, and participants at the SOLE meeting and the Royal Statistical Society's "Explanations for Rising Economic Inequality" conference in November 2001 for comments, suggestions, and criticisms. Card's research was supported by grants from the National Science Foundation and the National Institute of Child Health and Development.*

The industrial revolution of the eighteenth and nineteenth centuries left in its wake a large body of literature, both popular and scholarly, arguing that technology had wrought fundamental changes to the labor market. Some argued that as important as the steam engine and new machinery were to this new economy, "mental steam power" and "intellectual machinery"—the ability of workers to interact with the new technologies—was of equal or greater significance. Even as debate about that earlier period continues more than one hundred years later, a new debate—with interesting parallels to that earlier discussion—has ensued about the effect of computers and other information and communications technology on the labor market.[1]

Developments in personal computers, for example, led *Time* magazine to make the device its 1982 "Person of the Year" and argue that "the information revolution . . . has arrived . . . bringing with it the promise of dramatic changes in the way people live and work, perhaps even in the way they think. America will never be the same." By the late 1980s and early 1990s, labor market analysts were finding it apparent that wage inequality had risen, and a series of papers argued that these two developments—rapid technological change and rising wage inequality—were related.[2] These papers and the large literature that followed have paved the way for the virtually unanimous agreement among economists that developments in computers and related information technologies in the 1970s, '80s, and '90s have led to increased wage inequality.

In the labor economics literature this consensus view has become known as the "skill-biased technological change" (SBTC) hypothesis. Specifically, this hypothesis is the view that a burst of new technologies led to an increased demand by employers for highly skilled workers (who are more likely to use computers) and that this increased demand led to a rise in the wages of the highly skilled relative to those of the less skilled and therefore an increase in wage inequality.

In this paper, which is a substantially abridged version of Card and DiNardo (2002), we reconsider the evidence for the SBTC hypothesis. We focus considerable attention on changes over time in overall wage inequality and in the evolution of relative wages of different groups of workers. In doing so, we conclude that despite the considerable attention this view has received in the literature, SBTC falls far short of unicausal explanation of the substantial changes in the U.S. wage structure of the 1980s and 1990s. Indeed, although there have been substantial changes in the wage structure in the last thirty years, many of which are documented here, SBTC by itself does not prove to be particularly helpful in organizing or understandings these changes. Based on the evidence, we conclude that it is time to reevaluate the case that SBTC offers a satisfactory explanation for the rise in U.S. wage inequality in the last quarter of the twentieth century.

An Empirical Framework for Understanding SBTC

There are many theoretical versions of skill-biased technological change. To help fix ideas, this paper focuses on a simple SBTC formulation, versions of which have helped guide the large empirical literature in labor economics.[3] Assume that aggregate labor demand is generated by a constant elasticity of substitution (CES) production function of the form

$$(1)\quad Y = f(N_H, N_L) = A\,[\alpha(g_H N_H)^{(\sigma-1)/\sigma} + (1-\alpha)(g_L N_L)^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)},$$

where Y represents the value of output; N_H represents the labor input (employment or hours) of high-skilled workers; H_L represents the input of low-skilled labor; $\sigma > 0$ is the elasticity of substitution between the labor inputs; and A, α, g_H, and g_L are technological parameters that can vary over time.[4] In many empirical applications N_H is measured by the number of college graduates (or "college-equivalent" workers), and N_L is measured by the number of high-school graduates (or "high-school-equivalent" workers.) For given values of the technology parameters, the relative demand for high-skilled labor is determined by setting the ratio of the marginal product of the two groups equal to the ratio of their wages, w_H/w_L. Taking logarithms of the resulting expression and first-differencing over time leads to a simple expression that has been widely used to discuss the evolution of relative wages:

$$(2)\quad \Delta\log[w_H/w_L] = \Delta\log[\alpha/(1-\alpha)] + (\sigma-1)/\sigma\Delta\log[g_H/g_L] - 1/\sigma\Delta\log[N_H/N_L].$$

The equation is assumed to hold true for every time period (typically a year). If the relative supply of the two skill groups is taken as exogenous, this equation completely determines the evolution of relative wages over time. The technological parameters cannot be observed directly but are often inferred by making some assumptions about how they evolve over time. From equation 2, two observations follow directly.

First, changes in relative wages must reflect either changes in relative supplies or changes in technology. Other features of the labor market that potentially affect relative wages (such as the presence of unions, institutional wage floors, etc.) are essentially ignored. In the absence of technological change, the relative wage of high-skilled workers varies directly with their relative supply. Despite some problems of identification, there exists a "consensus" estimate of $\sigma \approx 1.5$ when the two skill groups are college and high-school workers.[5] This estimate implies, for example, that a 10 percent increase in the relative proportion of college-educated workers lowers the relative wage of college-educated workers by 6.6 percent. Since the relative proportion of highly educated workers has been rising throughout the past several decades, the only way to explain a rise in the relative wage of skilled workers (and hence a rise in wage inequality) is through changes in the technology parameters α or g.

Second, skill-biased changes in technology lead to changes in wage inequality. A shift in the parameter A, or an equiproportional shift in g_H and g_L, leaves the relative productivity of the two skill groups unchanged and affects only the general level of wages. SBTC involves either an increase in α or an increase in g_H relative to g_L. A rise in α raises the marginal productivity of skilled workers and at the same time lowers the marginal productivity of unskilled workers. This type of technological change has been referred to as "extensive" SBTC; Johnson (1997) gives as an example of extensive SBTC the introduction of robotics in manufacturing. The other situation, sometimes referred to as "intensive" SBTC, arises when technological change enhances the marginal productivity of skilled workers without necessarily lowering the marginal product of unskilled workers.[6]

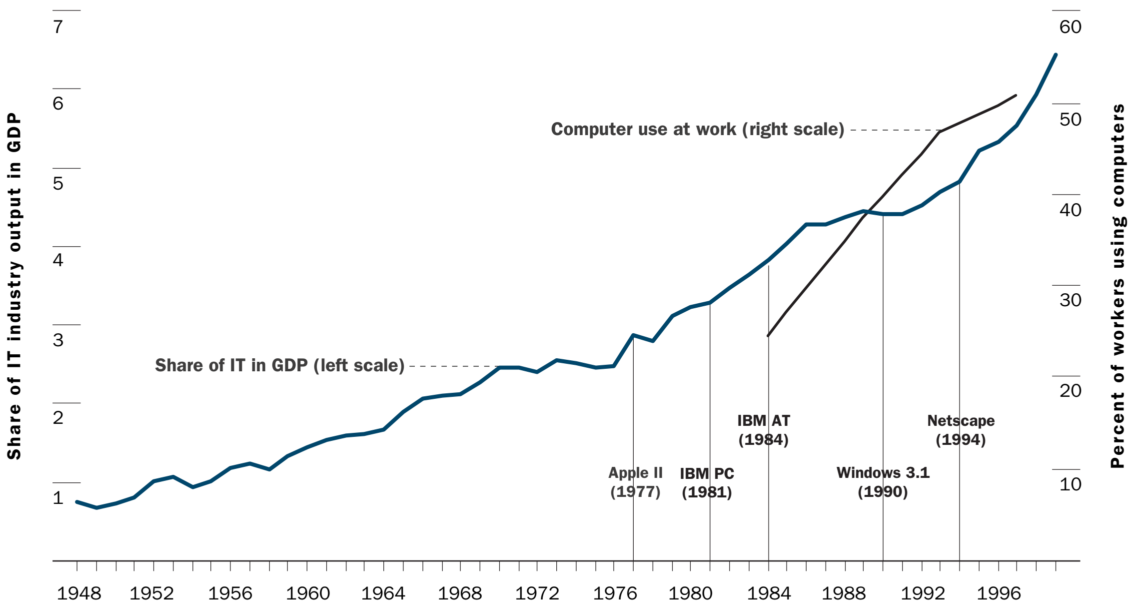
Technology or Tautology?

As has been observed, in this framework SBTC can be defined to exist whenever changes in relative wages are not inversely related to changes in relative supply. Indeed, the test for SBTC proposed by Katz and Murphy (1992) is a multifactor version of this point. Given a priori qualitative or quantitative evidence on how different skill groups are affected by changes in technology, however, the SBTC hypothesis can be tested using data on relative wages and relative labor supplies of different education/age groups, and we proceed to do so in a number of ways.

Aggregate trends in technology. A first task in making the SBTC hypothesis testable is to quantify the pace of technological change. The most widely cited source of SBTC in the 1980s and 1990s is the personal computer (PC) and related technologies, including the Internet. Chart 1 presents a timeline of key events associated with the development of personal computers, plotted with two simple measures of the extent of computer-related technological change. Although electronic computing devices were

CHART 1

Measures of Technological Change



Source: Jorgenson (2001) and authors' analysis of October Current Population Survey, various years

developed during World War II, and the Apple II was released in 1977, many observers date the beginning of the computer revolution to the introduction of the IBM-PC in 1981. This development was followed by the IBM-XT (the first PC with built-in disk storage) in 1982 and the IBM-AT in 1984. As late as 1989, most personal computers used Microsoft's disk operating system (DOS). More advanced graphical-interface operating systems gained widespread use only with the introduction of Windows 3.1 in 1990.

Some analysts have drawn a sharp distinction between stand-alone computing tasks (such as word-processing or database analysis) and organization-related tasks (such as inventory control, supply-chain integration, and internet commerce) and argue that innovations in the latter domain are the major source of SBTC.[7] This reasoning suggests that the evolution of network technologies is at least as important as the development of personal computer technology. The first network of mainframe computers (the ARPANET) began in 1970 and had expanded to about 1,000 host machines by 1984.[8] In the mid-1980s the National Science Foundation laid the backbone for the modern Internet by establishing NSFNET. Commercial restrictions on the use of the Internet were lifted in 1991, and the first U.S. site on the World-Wide Web was launched in December 1991.[9] Use of the Internet grew very rapidly after

1. See Berg and Hudson (1992) and Crafts and Harley (1992) for two very different views of the industrial revolution.
2. See, for example, Bound and Johnson (1992); Juhn, Murphy, and Pierce (1993); Levy and Murnane (1992); and Katz and Murphy (1992).
3. See, for example, Bound and Johnson (1992); Berman, Bound, and Griliches (1994); and Autor, Katz, and Krueger (1998). For a more complete discussion, see the longer version in Card and DiNardo (2002).
4. This model can be easily extended to include capital or other inputs provided that labor inputs are separable and enter the aggregate production function through a subproduction function like equation 1.
5. See Katz and Murphy (1992) and Autor and Katz (1999).
6. Note that it is necessary to assume $\sigma > 1$ in order for a rise in g_H relative to g_L to increase the relative wage of skilled workers. The distinction between the four parameters (A, α, g_H, g_L) is somewhat artificial because one can always rewrite the production function as $Y = [c_H N_H^{(\sigma-1)/\sigma} + c_L N_L^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)}$ by suitable definition of the constants c_H and c_L. The relevant question is how the pair (c_H, c_L) evolves over time.
7. This distinction is emphasized by Bresnahan (1999) and Bresnahan, Brynjolfsson, and Hitt (2002).
8. See Hobbes' Internet Timeline at www.zakon.org/robert/internet/timeline.
9. The World-Wide Web was invented at CERN (the European Laboratory for Particle Physics) in 1989–90.

the introduction of Netscape's Navigator program in 1994: The number of Internet hosts rose from about one million in 1992, to twenty million in 1997, and to one hundred million in 2000.

Qualitative information on the pace of technological change is potentially helpful in drawing connections between specific innovations and changes in wage inequality. For example, the sharp rise in wage inequality between 1980 and 1985 (discussed below) points to technological innovations that occurred very early in the computer revolution (around the time of the original IBM-PC) as the key skill-biased events. By comparison, innovations associated with the growth of the Internet presumably had very limited impact until the mid-1990s. Nevertheless, comparisons of relative timing are subject to substantial leeway in interpretation, depending on lags in the adoption of new technologies.

While some of the early rise in inequality may have been due to rapid technological change, we suspect that the increase in the early 1980s is largely explained by other plausible—albeit relatively mundane—factors.

An alternative approach is to attempt to quantify recent technological changes by measuring the relative size of the information technology (IT) sector in the overall economy. One such measure, taken from Jorgenson (2001), is plotted in Chart 1. Notwithstanding the obvious difficulties with the interpretation of such a simplified measure by a fairly broad measure—IT output as a percentage of total gross domestic product—information technology has grown steadily in importance since 1948, with sustained growth over the past two decades and a pronounced upsurge in the late 1990s.[10] The rapid expansion of the IT sector in the late 1990s has attracted much attention, in part because aggregate productivity growth rates also surged between 1995 and 2000. Many analysts (including Basu, Fernald, and Shapiro 2001) have argued that this was the result of an intensive burst of technological change in the mid- to late 1990s.

A third approach, pioneered by Krueger (1993), is to measure the pace of computer-related technological change by the fraction of workers who use a computer on the job. The thin black line in Chart 1 plots the overall fraction of workers who reported using a computer in 1984, 1989, 1993, and 1997.[11] Rates of on-the-job computer use, like the IT output share, show substantial growth over the past two decades—from 25 percent in 1984, to 37 percent in 1989, and to 50 percent in 1997. Nevertheless, the fact that one-quarter of workers were using computers on the job in 1984 suggests that some of the impact of computerization on the workforce preceded the diffusion of personal computers. Indeed, Bresnahan (1999) has estimated that as early as 1971 one-third of U.S. workers were employed in establishments with mainframe computer access. Specialized word-processing machines that predated the personal computer were also widely in use in the early 1980s. The absence of systematic data prior to 1984 makes it hard to know whether computer use expanded more quickly in the early 1980s than in the late 1970s or the late 1980s, which in turn makes it difficult to compare changes in the rate of computer use with changes in wage inequality, especially in the critical early years of the 1980s.[12]

While none of the available indicators of technological change is ideal, all of the indicators suggest that IT-related technological change has been going on since at least the 1970s and has continued throughout the 1980s and 1990s. Moreover, some evidence (based on the size of the IT sector, the pace of innovations associated with the Internet, and aggregate productivity growth) suggests that the rate of technological change accelerated in the 1990s relative to the 1980s.

Whose productivity was raised by recent changes in technology? The second task in developing an empirically testable version of the SBTC hypothesis is to specify which skill groups have their relative productivity raised by SBTC. There are two main approaches to this issue. The first, articulated by Autor, Katz, and Krueger (1998), is to assume that groups that are more likely to use computers have skills that are more complementary with computers and experience bigger gains in productivity with continuing innovations in computer technology.[13] We refer to this as the "computer-use/skill-complementarity" view of SBTC. An alternative, advanced by Juhn, Murphy, and Pierce (1991, 1993), is to assume that recent technological changes have raised the relative productivity of more highly skilled workers along every dimension of skill, leading to an expansion of the wage differentials between groups.[14] We refer to this as the "rising-skill-price" hypothesis. As it turns out, the two approaches yield similar implications for comparisons across some dimensions of the wage structure but different implications for others. Throughout, we will refer to either version or both versions of SBTC as appropriate.

To set the stage, the table on page 50 shows patterns of relative computer use on the job by different skill groups in 1984, 1989, 1993, and 1997. Rates of computer use tend to be higher for those with more schooling. High-school graduates are three to four times more likely to use computers on the job than dropouts, and college graduates are about twice as likely to use computers as those with only a high-school diploma. Interestingly, although overall computer use rates have risen, the relative usage rates of different education groups have remained fairly stable. Since the wage differentials between education groups are bigger today than at the start of the 1970s, this fact would appear to be consistent with the computer-use/skill-complementarity view. Moreover, since better-educated workers earn higher wages, an increase in the wage differential between the highly and less highly educated is also consistent with the rising-skill-price view of SBTC.

The data in the table also show that women are more likely to use computers at work than men, and blacks are less likely to use computers than whites. Although the gender and race gaps closed slightly in the early 1990s, the male-female and black-white gaps remain relatively large. To the extent that complementarity with computer-based technologies is measured by computer use rates, these patterns suggest that recent technological changes should have led to upward pressure on women's wages relative to men's and downward pressure on black workers' wages relative to whites'. In the case of the race differential, the relative wage approach to gauging the impact of SBTC leads to a similar conclusion.[15] In the case of the gender differential, however, the two methods are inconsistent. Women earn less than men and, as with the racial wage gap, part of the gender gap is usually attributed to differences in unobserved skills. Thus, the argument that recent technological changes have raised the relative productivity of more highly paid workers—the rising-skill-price view of SBTC—suggests that computer technology should have led to a widening of the male-female wage gap.

Simple tabulations of computer use rates by education and gender hide an important interaction between these two factors, however. The education gradient in computer use is much bigger for men than women while differences in computer use by gender are much smaller for better-educated workers. Indeed, as shown in the table, college-educated men are more likely to use a computer than college-educated women. To the extent that computer use indexes the relative degree of complementarity with new technology, as assumed by the computer-use/skill-complementarity version of SBTC, computer technology should have widened gender differentials for the most highly educated and narrowed them for the least educated. By contrast, since men earn more than women at all educational levels, the rising-skill-price view of SBTC suggests that the gender gap should have expanded at all educational levels. Although the data are not reported in the table, we have also examined the interactions between gender and race. Compared to the interaction between education and gender, however, the race-gender interactions are relatively modest.

Finally, an examination of computer use rates by age suggests that computer use has expanded slightly faster for older workers than for younger workers. As shown in more detail in Card and DiNardo (2002), computer use rates in the early 1980s were declining slightly with age. By the late 1990s, however, the age profile of computer use was rising slightly between the ages of twenty and forty-five and declining after age fifty. These observations suggest another divergence between the two versions of SBTC. Based on the age profiles of computer use, SBTC may have led to a reduction in older workers'

10. See Oliner and Sichel (2000) and Gordon (2000) for interesting discussions of some of these issues.

11. These data are based on responses to questions in the October Current Population Surveys for workers estimated to be out of school. See Card and DiNardo (2002) for details.

12. Card and DiNardo (2002), using data from the Information Technology Industry (ITI) Council on annual shipments of different types of computers since 1975, find that series constructed from this data show fairly steady growth in shipments from 1975 to 1984.

13. Note that this hypothesis does not necessarily imply that individuals who use computers will be paid more or less than people in the same skill group who do not.

14. To be slightly more formal, assume that the log of the real wage of individual i in period t (w_{it}) is a linear function of a single index of individual ability $a_i = x_i\beta + u_i$, where x_i is a set of observed characteristics and u_i represents unobserved characteristics. Then $\log(w_{it}) = p_t a_i = x_i(p_t\beta) + p_t u_i$, where p_t is the economywide "price" of skill. Skill-biased technological change in the rising-skill-price view is merely an increase over time in p_t.

15. Juhn, Murphy, and Pierce (1991) argued that blacks tend to have lower levels of unobserved ability characteristics and that rising returns to these characteristics held down relative wages for blacks in the 1980s.

TABLE

Use of Computers at Work (Percent)

	1984	1989	1993	1997
All workers	24.5	36.8	46.0	49.9
By education				
Dropouts	4.8	7.4	8.9	11.3
High school	19.8	29.2	34.0	36.1
Some college	31.9	46.4	53.5	56.3
College (or more)	41.5	57.9	69.1	75.2
High school/college	47.7	50.5	49.1	48.1
By gender				
Men	21.1	31.6	40.3	44.1
Women	29.0	43.2	52.7	56.7
Male/female	73.0	73.2	76.5	77.8
By gender and education				
High-school men	12.9	20.1	24.1	26.8
College men	42.7	58.8	70.5	75.5
High-school women	27.5	39.2	45.1	46.8
College women	39.6	56.6	67.4	74.7
High school/college (men)	30.2	34.2	34.2	35.5
High school/college (women)	69.4	69.3	66.9	62.7
Male/female (high school)	46.9	51.3	53.4	58.3
Male/female (college)	107.8	103.9	104.5	101.1
By race				
Whites	25.3	37.9	47.3	51.3
Blacks	18.2	27.2	36.2	39.9
Other	23.7	36.0	42.3	48.2
Black/white	72.1	71.7	76.7	77.7
By age				
Under 30	24.7	34.9	41.4	44.5
30–39	29.5	42.0	50.5	53.8
40–49	24.6	40.6	51.3	54.9
50 and older	17.6	27.6	38.6	45.3

Notes: Entries display percentage of employed individuals who answer that they "directly use a computer at work" in the October Current Population Survey (CPS) Computer Use Supplements. Samples include all workers with at least one year of potential experience. College workers include those with a college degree or higher education. All tabulations are weighted by CPS sample weights.

relative wages. On the other hand, since older workers earn more than younger workers, the rising-skill-price view of SBTC predicts a rise in age- or experience-related wage premiums over the 1980s and 1990s.

In what follows, we briefly review some important changes in wage inequality and in the wage structure. Throughout we will discuss both problems and puzzles for SBTC. The problems are facts that seem superficially inconsistent with both (either) version of the theory; the puzzles are important developments in the wage structure that are potentially consistent with SBTC but appear to be driven by other causes.

Trends in Overall Wage Inequality

Although measurement of wage inequality is substantially more straightforward than the measurement of technological change, there are a number of potentially important issues. The Current Population Survey (CPS) that is the most widely

CHART 2

Alternative Measures of Aggregate Wage Inequality

Source: Authors' analysis of March, May, and Outgoing Rotation Group files from monthly Current Population Survey and EPI

used source for data on individual wages (and the source we use here), for instance, experienced a substantial redesign in the mid-1990s that appears to have raised measured inequality. Nonetheless, our most important findings appear robust to choice of data sets and a variety of different methodologies for the measurement of inequality.[16]

Chart 2 plots three different measures of aggregate wage dispersion. The first is the standard deviation of log annual earnings for full-time full-year (FTFY) male workers, constructed from March CPS data from 1968 to 2001.[17] The second is the normalized 90-10 log wage gap in hourly earnings, based on the May CPS files for 1973 to 1978 and the OGR files from 1979 onward. This series is based on estimates constructed by the Economic Policy Institute (EPI), using procedures very similar to ours.[18] The third is the standard deviation of log hourly wages for all workers in the March CPS files from 1976 to 2001, weighted by the hours worked in the previous year.

An examination of the chart suggests that the recent history of U.S. wage inequality can be divided into three episodes. During the late 1960s and 1970s, aggregate wage inequality was relatively constant. The standard deviation of log wages for FTFY men rose by only 0.01 between 1967 and 1980 (from 0.51 to 0.52).[19] Wage inequality measures from the May CPS/OGR series also show relative stability (or even a slight decline) between 1973 and 1980 while the hours-weighted standard deviation of log hourly wages for all workers in the March CPS was stable from 1975 to 1980. The 1980s was a period of expanding inequality, with most of the rise occurring early in the decade. Among FTFY men, for example, 85 percent of the 10-point rise in the standard deviation of log wages between 1980 and 1989 occurred before 1985. Finally, in the late 1980s wage inequality appears to have stabilized. Indeed, none of the three series in Chart 2 shows a noticeable change in inequality between 1988 and 2000.

16. Card and DiNardo (2002) discuss at length issues of measurement and the robustness of the findings to alternative data sources and measurement methodologies.

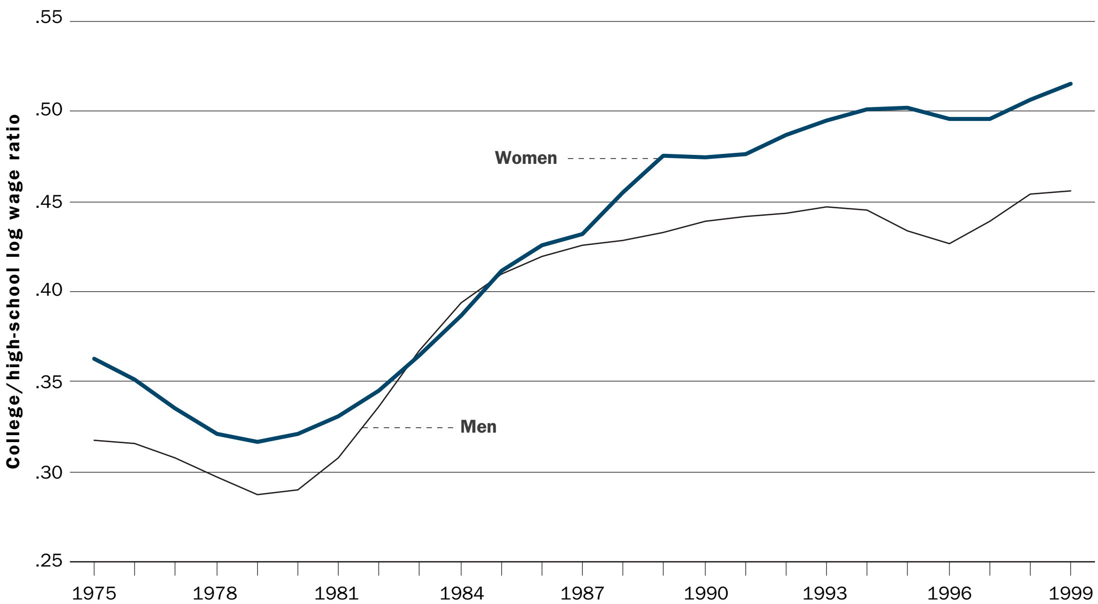
17. Here and in what follows, we refer to the data derived from the March supplement to the CPS as the March CPS and the data from the Outgoing Rotation Group files and the 1973–78 May supplements as the OGR and May CPS data, respectively. See Card and DiNardo (2002) for more details.

18. See Mishel, Bernstein, and Schmitt (2001, table 2.17). For details on this and all other aspects of the data, see Card and DiNardo (2002).

19. Similarly, the standard deviation of log wages for all full-time workers (men and women) was slightly lower in 1980 than in 1967.

CHART 3

College/High-School Wage Ratio by Gender, 1975–99



Source: Authors' analysis of March Current Population Survey, various years

The apparent stability of aggregate wage inequality over the 1990s presents a potentially important puzzle for the SBTC hypothesis, since there were continuing advances in computer-related technology throughout the decade that were arguably as skill biased as the innovations in the early 1980s.

Another interesting feature of the series in Chart 2 is that the rise in wage inequality over the 1980s was larger for FTFY men than for workers as a whole. While the reasons for this are unclear, if viewed with an eye toward SBTC, the relative rise in inequality for FTFY men is a puzzle. To the extent that SBTC tends to widen inequality across skill and ability groups, we would expect to see a larger rise in inequality for less homogeneous samples (for example, pooled samples of men and women and full- and part-time workers) and a smaller rise for more homogeneous samples (such as FTFY men). The data suggest the opposite.[20]

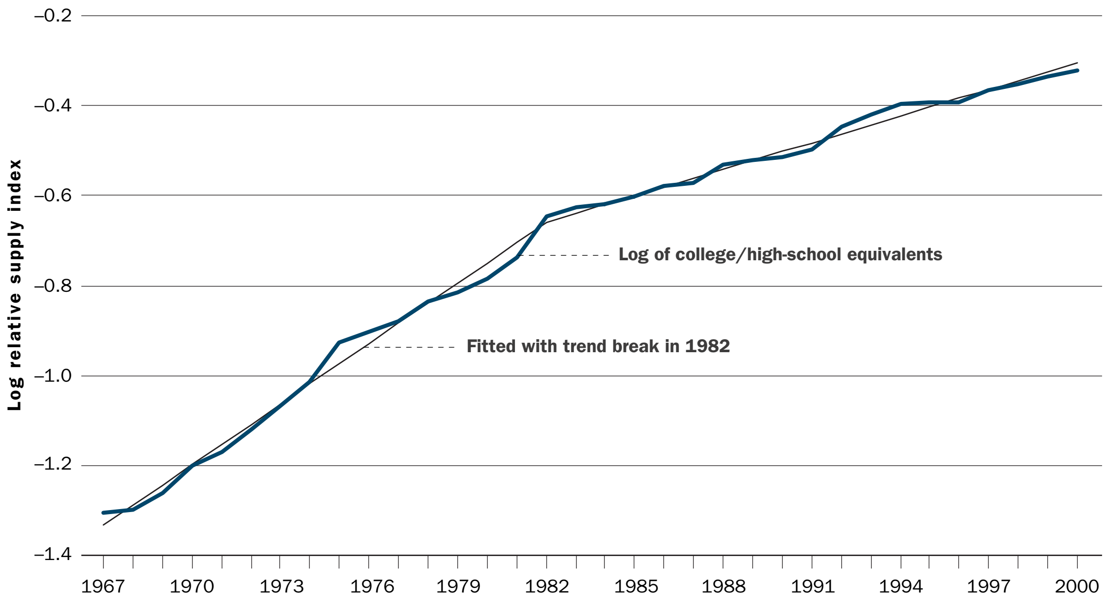
Components of the Wage Structure

Returns to college. We now shift our focus to specific dimensions of the wage structure. We begin with wage differences by education, which are at the core of the SBTC hypothesis. Chart 3 presents estimates of the college/high-school wage gap by gender for the 1975–99 period, based on average hourly earnings data from the March CPS.[21] Trends in the college/high-school gap are similar to the trends in overall inequality and suggest three distinct episodes: the 1970s, when the college gap was declining slightly; the 1980s, when the gap rose quickly; and the 1990s, when the gap was stable or rising slightly. For both men and women, the college/high-school wage gap rose by about 0.15 log points between 1980 and 1990. The rise for men was concentrated in the 1980–85 period while for women it was more evenly distributed over the decade. The similar overall rise in returns to college for men and women is interesting, however, because as noted earlier there is a much larger education gradient in computer use rates for men than women. Based on this fact, the computer-complementarity version of the SBTC hypothesis would predict a larger rise in the college/high-school wage gap for men than for women during the 1980s and 1990s. On the other hand, since the college/high-school wage gaps are similar for men and women, the skill-price version of SBTC predicts about the same rise in returns for both. Thus, the similarity of the rise in the college gap for men and women is a puzzle for one version of the theory but not for the other.

Some previous authors have argued that variation in the college/high-school wage premium can be explained by a model like equation 2, with the added assumption that the effect of changing technology follows a smooth trend (see, for example, Freeman 1975 and Katz and Murphy 1992). In these

CHART 4

Relative Supply of College-Educated Labor



Source: Authors' analysis of the March Current Population Survey, various years. See Card and DiNardo (2002) for details.

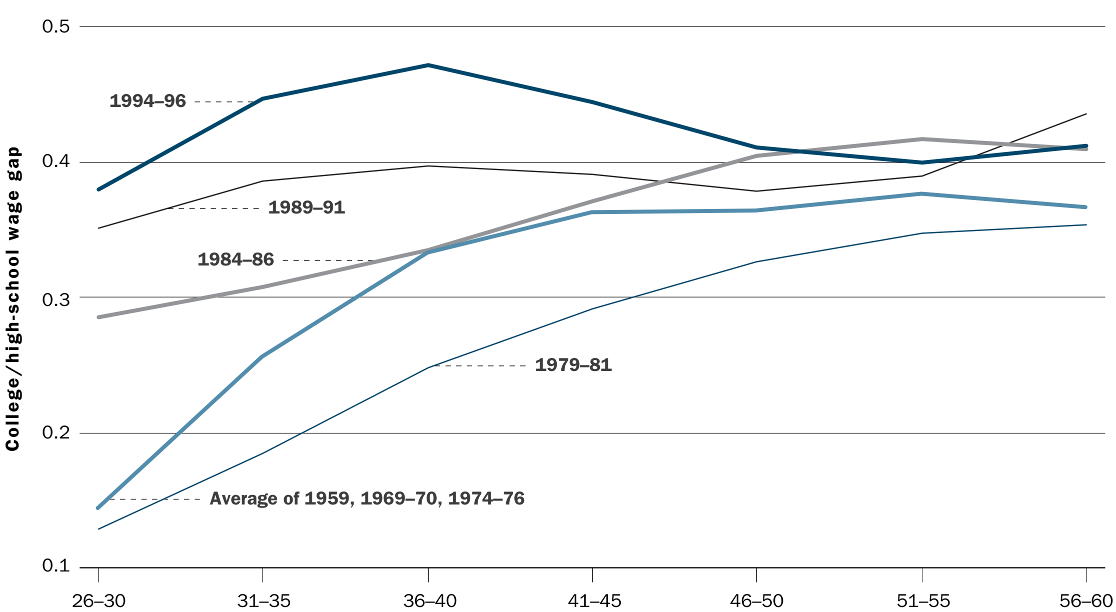
studies the relative supply of college workers is estimated by assigning various fractions of "college-equivalent" and "high-school-equivalent" labor units to workers in different education categories.[22] Using a variant of this method, we derive such a supply index, which is displayed in Chart 4. A feature of this index—which is revealing about a potential problem with the SBTC hypothesis—is that it follows a roughly constant trend between 1967 and 1982 (4.5 percent per year) and a slower but again nearly constant trend after 1982 (2.0 percent per year).[23] Assuming that $1/\sigma$ is positive, shifting trends in relative supply can potentially explain an upward shift in the rate of growth of the college/high-school wage gap in the early 1980s but not the slowdown in the 1990s.

The problem is further revealed by comparing estimates of models based on equation 2 that exclude or include the 1990s. For example, augmenting the model with a trend shift term that allows for a possible acceleration in SBTC after 1980, the estimate of the relative supply term becomes wrong-signed, and the model substantially overpredicts returns to college in the late 1990s.[24] We conclude that the slowdown in the rate of growth in the return to college in the 1990s is a problem for the SBTC hypothesis that cannot be easily reconciled by shifts in relative supply.

20. As we explain in the longer version of this paper, although we prefer to measure aggregate wage inequality using the broadest possible sample of workers, the tradition in the inequality literature has been to analyze men and women separately (although Lee 1999 and Fortin and Lemieux 2000 are important counterexamples). Treating men and women separately, however, yields substantially the same conclusions for men. For women the trends in inequality are a little different although they pose essentially the same problems for SBTC. For instance, whether the OGR or March data are used, it is clear that most of the rise in gender-specific wage inequality, like the rise in overall inequality, was concentrated in the first half of the 1980s, with surprisingly little change in the 1990s.
21. These estimates are obtained from regression models fit separately by gender and year to samples of people with either twelve or sixteen years of education. The models include a dummy for college education, a cubic in years of potential experience, and a dummy for nonwhite race.
22. For example, a worker with fourteen years of education contributes one-half unit of college labor and one-half unit of high-school labor while a worker with ten years of education contributes something less than one unit of high-school labor.
23. Indeed, a regression of the supply index on a linear trend and post-1982 trend interaction yields an R^2 of 0.997.
24. See Card and DiNardo (2002.) Beaudry and Green (2002) experiment with several variants of equation 2 and report similar findings.

CHART 5

Changing Age Structure of the College/High-School Wage Gap



Source: Card and Lemieux (2001)

Education and age. So far we have focused on the average difference in wages between college and high-school workers in all age groups. This focus arises naturally out of a model such as the one described by equations 1 and 2, where there are only two skill groups—high and low education—and workers with different years of labor market experience are treated as perfect substitutes. In such a model, there is a unique "return to education" in the economy as a whole at any point in time. Moreover, the focus on average returns to college is descriptively adequate whenever the wage differentials between education groups are the same for people with different ages or different years of experience, as in Mincer's (1974) human capital earnings function.[25]

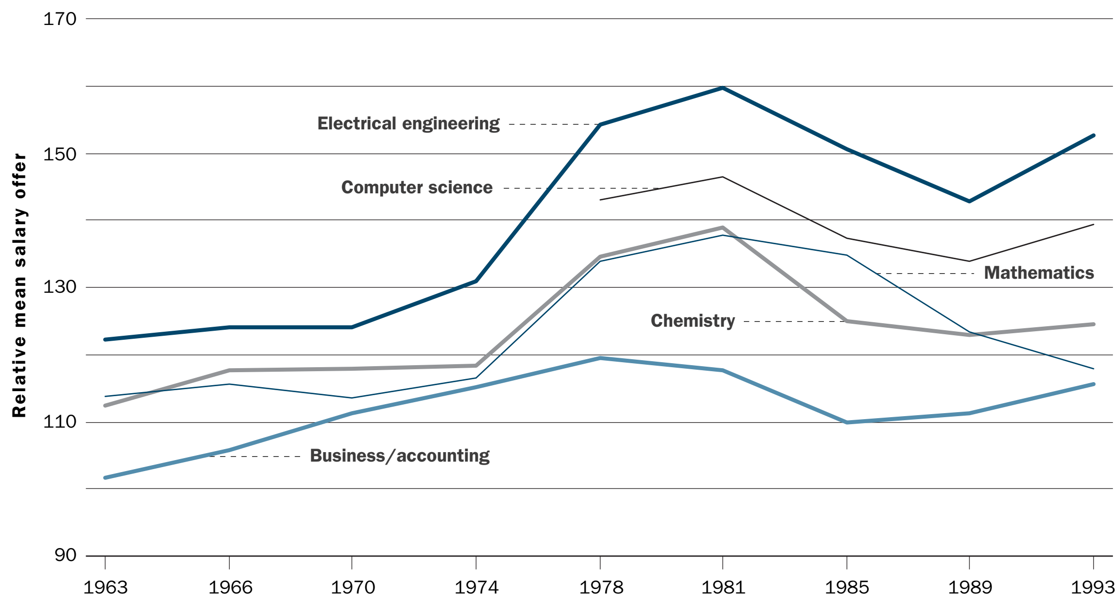
While the rise in the average wage gap between college and high-school workers has been extensively documented, the fact that the increases have been very different for different age groups is less well known. Specifically, the rise in the college/high-school wage gap for men is most pronounced among young workers entering the labor force after the late 1970s. Moreover, the pattern of this increase does not appear to be well explained by either the rising-skill-price or computer-use/skill complementarity versions of SBTC.

One assumption embedded in equation 1 is that workers with similar educations but different ages are perfect substitutes in production. Card and Lemieux (2001) show that one implication of a more general model that allows for imperfect substitution across age groups is the presence of cohort effects in the returns structure. Because education is (essentially) fixed once a cohort enters the labor market, a cohort with fewer highly educated workers will experience higher relative returns at each age, leading to cohort-specific deviations from the average pattern. Evidence of such cohort effects is presented in Chart 5 (taken from Card and Lemieux 2001), which shows the age profiles of the college/high-school wage gap for five-year age cohorts of men in five periods: 1960–76 (based on pooled data from the 1960 Census and early CPS surveys), 1979–81, 1984–86, 1989–91, and 1994–96. In the 1960s and early 1970s the college/high-school wage gap was an increasing and slightly concave function of age, consistent with the functional form posited by Mincer (1974). Subsequent changes in the age structure of the college/high-school gap, however, reveal a "twisting" of the age profile—large increases in the gap at relatively young ages during the mid-1980s to the mid-1990s and relatively small changes in the gap for older men.

Based on the data in Chart 5 and a series of formal statistical tests, Card and Lemieux (2001) argue that the trends in the college/high-school wage gap for different age groups reflect systematically higher college/high-school wage premiums received by successive cohorts that have entered the labor market since the late 1970s. Moreover, these cohort effects

CHART 6

Mean Salary Offer Relative to Humanities/Social Sciences



Source: Authors' analysis of data from National Association of Colleges and Employers

are highly correlated with cohort-specific changes in the relative supply of college workers. Somewhat surprisingly, after controlling for cohort-specific supplies, they find that the return to education was about the same in the mid-1990s as it had been in the mid-1970s. This interpretation of the data leaves little or no room for accelerating technical change; while one could argue that the spread of computers led to cohort-specific relative productivity gains for college-educated workers, there is no direct evidence of such a phenomenon. Moreover, the age profiles of the college/high-school gap in computer use shifted uniformly between 1984 and 1997, rather than twisting like the returns profiles in Chart 5.

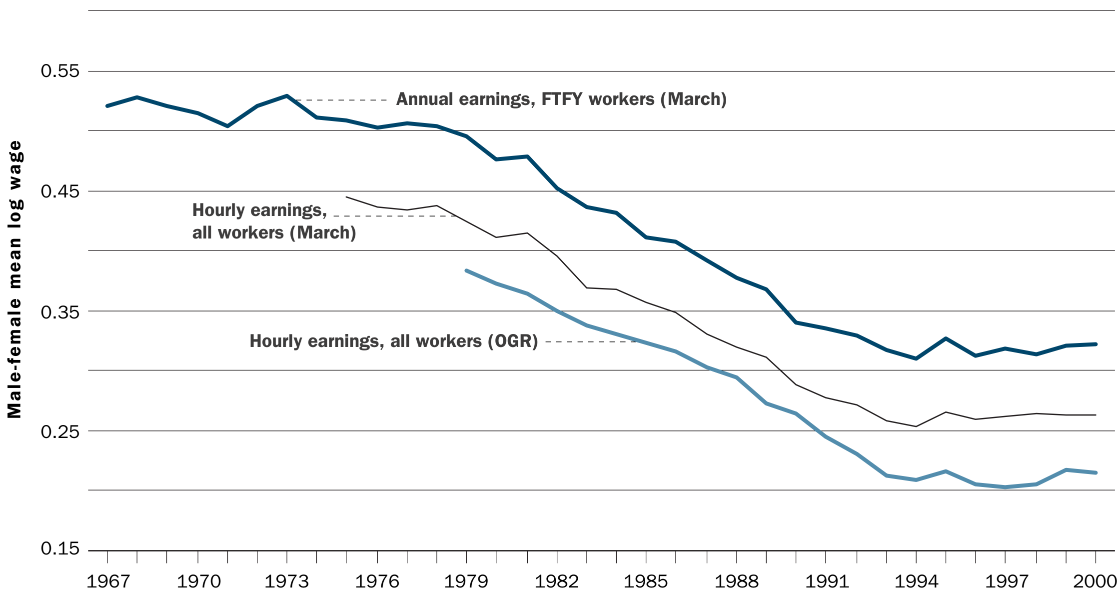
Returns to different college degrees. One concern with evidence for SBTC based on overall wage differences between college and high-school workers is that computer-related technology may have had different effects on college graduates from different fields of study. In particular, it seems plausible that the computer revolution would lead to a rise in the relative demand for college graduates with more "technical" skills (like engineers and scientists), especially in the early 1980s when microcomputers were first introduced and the college/high-school wage gap was expanding rapidly. Chart 6 displays mean starting salaries offered to graduating students with bachelors degrees in various fields, compiled from a survey of career placement offices conducted by the National Association of Colleges and Employers, and brings some evidence to bear on this possibility.[26] For convenience, we have scaled the data to show mean salaries relative to humanities and social sciences. The most obvious feature of the data is that the relative salaries in more technical fields rose in the 1970s and fell in the 1980s. This pattern is particularly true for the relative salaries in the two fields most closely connected with computers: computer science and electrical engineering. Paradoxically, the introduction of microcomputers was associated with a fall in the relative salaries of specialized college graduates with the strongest computer skills. Although the data in Chart 6 cover only the period up to 1993, more recent data suggest that in the late 1990s the relative salaries of electrical engineering and computer

25. The simplest way to justify Mincer's formulation within the framework of the model in equation 1 is to assume that the relative efficiency units of different age groups depend only on experience (for example, age minus education) and that the relative efficiency profile is the same for college and high-school labor.

26. An alternative data source on college graduates' relative salaries in different fields, the Recent College Graduates Survey (which is available only since 1977), shows similar patterns. See U.S. Department of Education (1998, supp. table 33-1).

CHART 7

Male-Female Wage Gaps



Source: Authors' analysis of March and May Current Population Survey, various years, and Outgoing Rotation Group files from monthly Current Population Survey, various years

science graduates rose back to the levels of the late 1970s. Thus, the IT-sector boom in the late 1990s was associated with a rise in relative wages of graduates with computer-related skills.

We regard the trends in the relative salaries of college graduates in different fields as at least a puzzle, if not a problem, for the SBTC hypothesis. While innovations in computer technology do not necessarily raise the relative demand for workers with the most specialized computer training, engineers and computer scientists have very high rates of computer use and also earn higher wages than other bachelor degree holders. Thus, the decline in the wage premium for engineers and computer science graduates over the 1980s is inconsistent with either the computer-use/skill-complementarity or rising-skill-price versions of the SBTC hypothesis.

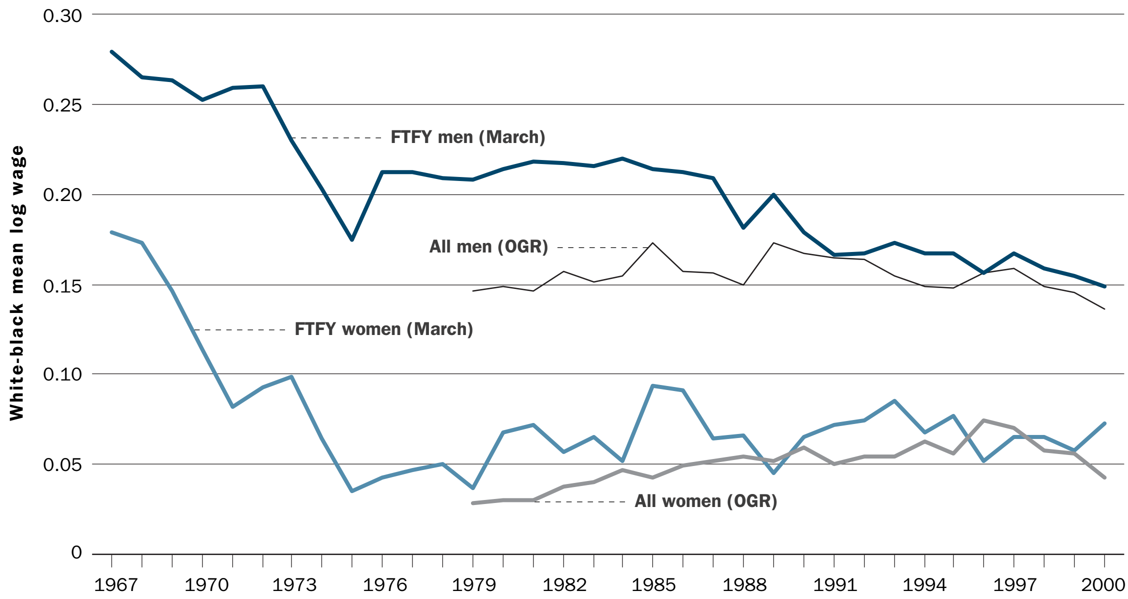
Other Changes in the Structure of Wages

The male-female wage gap. One of the most prominent changes in the U.S. wage structure is the recent closing of the male-female gap. Chart 7 displays three estimates of the gap in wages between men and women: the difference in mean log annual earnings of full-time/full-year workers (based on March CPS data); the difference in mean log average hourly earnings from the March CPS (for 1975 and later); and the difference in mean log average hourly earnings from the OGR supplements (for 1979 and later). Like overall inequality and returns to college, trends in the male-female wage gap seem to fall into three distinct episodes. During the 1970s, the gender gap was relatively stable. During the 1980s and early 1990s the gap fell. Finally, in the mid- to late-1990s the gap was stable again. Although the different wage series give somewhat different estimates of the size of the gender gap, all three show a 15 percentage point decline between 1980 and 1992. Moreover, these trends are very similar for different age and education groups.

These trends, and their similarity for different age and education groups, pose a number of problems and puzzles for different versions of the SBTC hypothesis. As noted earlier, the closing of the gender gap in the 1980s is a particular problem for the rising-skill-price version of SBTC, which predicts that technological change raises the return to all different kinds of skills, including the unobserved skills that are usually hypothesized to explain the gender gap. Since women use computers on the job more than men, some observers have argued that the decline in the gender wage gap *is* consistent with the computer-use/skill-complementarity version of SBTC.[27] This theory cannot explain the similarity of the trends in the gender gap for high-school and college graduates, however, since college-educated women are actually less likely to use a computer than college-educated men. Thus, like Blau and Kahn

CHART 8

White-Black Wage Gaps



Source: Authors' analysis of March and May Current Population Survey, various years, and Outgoing Rotation Group files from monthly Current Population Survey, various years

(1997), we conclude that the rise in women's wages relative to men's wages over the 1980s must be attributed to gender-specific factors.

The black-white wage gap. Chart 8 shows the evolution of another important dimension of wage inequality—the difference in wages between white and black workers. The chart shows the wage gaps for full-time/full-year men and women (derived from March CPS data) and for all men and women (based on average hourly earnings from the OGR data). The gaps for women are similar whether the data are confined to FTFY workers or not while the gaps for men are slightly different between FTFY workers and all workers, at least in the early 1980s. As previous studies have documented, racial wage gaps are also much smaller for women than for men. More interesting from our perspective are the trends in the racial wage gap, which are quite different from the trends in other dimensions of inequality. During the 1970s, when the gender gap and overall wage inequality were relatively stable, the wage advantage of white workers fell sharply: from 28 to 18 percent for men and from 18 percent to 4 percent for women. During the 1980s, when overall wage inequality was rising and the gender gap was closing, the black-white wage gap was relatively stable. Finally, over the 1990s, racial wage gaps were roughly constant. The gaps for high-school and college-educated men and women are similar to the corresponding gaps for all education groups and follow roughly similar trends.

Like the gender wage gap, we view the evolution of racial wage differences as at least a puzzle, and potentially a problem, for SBTC. Both the rising-skill-price view and the computer-use/skill-complementarity view suggest that SBTC should have led to a widening of racial wage gaps in the 1980s. The gap in computer use between blacks and whites is about the same magnitude as the male-female gap, so the same arguments that have been made about the effect of computerization on male-female wage differences would seem to apply to race. Indeed, Hamilton (1997) argues that a computer skills gap contributed to an increase in the wage differentials between whites and blacks. In view of the data in Chart 8, however, it is clear that other factors must have worked in the opposite direction to offset any such effects of SBTC.

Work experience. Along with education, gender, and race, a fourth key dimension of wage inequality in the U.S. labor market is age. Following Mincer (1974), most labor market analysts have adopted the

27. For example, Weinberg (2000) argues that "since computer [jobs] are likely to be less physically demanding than the average noncomputer job, the elimination of noncomputer jobs in which men have a comparative advantage and the creation of computer jobs in which women have a comparative advantage would tend to favor women."

assumption that log wages are a separable function of education and potential labor market experience (age minus education minus 6): In this framework, if there is an increase in the return to skill caused by changes in technology, we should expect the return to an additional year of experience to rise. As shown in more detail in Card and DiNardo (2002), here too the evidence is not favorable for SBTC. For example, there is little evidence of either a rise or fall in the average return to experience over the period 1979 to 1991 for high-school-educated men, who make up about one-third of all male workers. Much the same is true for younger college-educated men (those between the ages of twenty-four and thirty-seven who have two to fifteen years of potential experience), and for college-educated men in the middle range of experience, the wage profile actually became flatter over the 1980s and 1990s.

Given this analysis of the change (or lack of change) in men's experience profile, it is difficult to rationalize the somewhat different evolution of the potential experience profile for women in an SBTC framework. During the period 1979–91, experience profiles did become somewhat steeper for both high-school- and college-educated women, particularly for women with between two and eighteen years of potential experience. Manning (2001) has shown that for women in the United Kingdom, where the male-female wage gap also closed substantially over the 1980s, a similar increase in the returns to experience can be in part explained by a shift across cohorts in the fraction of time spent working.[28] How far such an analysis could go toward explaining the these shifts in the experience profile is an interesting question. In any case, we suspect that SBTC has little to do with the story.

Residual inequality. SBTC has also been proposed as an explanation for the rise in inequality among workers with similar observable characteristics. To the extent that wage differences between workers with the same education, age, gender, and race reflect the labor market's valuation of unmeasured productivity, the rising-skill-price version of SBTC predicts a rise in the residual variance associated with a standard human capital model of wage determination while the prediction from the computer-complimentarity version of SBTC is unclear. As documented in Card and DiNardo (2002), however, the trends in residual inequality pose much the same difficulties as the trends in overall inequality that we have documented here. In particular, we find that most of the modest rise in residual inequality was concentrated in the early 1980s, which suggests that if SBTC is the cause for this change, it occurred during the earliest years of the microcomputer revolution.

SBTC and Productivity

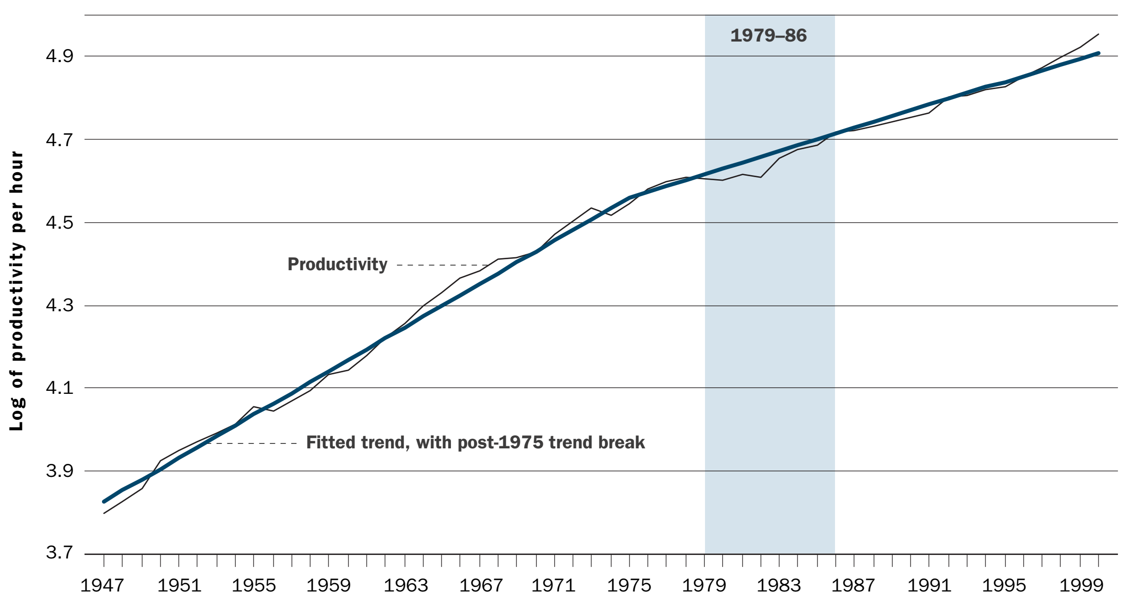
A final issue worth discussing is the relationship between SBTC and productivity growth. Many analysts have noted that the pace of aggregate productivity growth was stable during the 1980s and early 1990s despite the introduction of computers and the almost immediate effect that computerization is presumed to have had on wage inequality.[29] To illustrate, Chart 9 plots the log of real output per hour in the nonfarm business sector of the United States over the 1947–2000 period, along with a fitted trend line that allows a productivity slowdown after 1975.[30] The rate of labor productivity growth during the 1980s and early 1990s was substantially slower than in 1947–75. However, between 1979 and 1986, when aggregate wage inequality was expanding rapidly, productivity first fell relative to trend (during the 1980 and 1982–83 recessions), then recovered to its earlier trend level. There is no indication that developments in the early 1980s led to an unexpected change in the productive capacity of the economy.

We regard the absence of a link between SBTC (as measured by the rate of increase in wage inequality) and aggregate productivity growth as a puzzle, although not necessarily a problem, for SBTC. While some theoretical discussions of technological change assume that any new technology leads to an outward shift in the economywide production frontier, some specific versions of SBTC do not. Extensive SBTC—a rise in the share parameter α in the aggregate production function given in equation 1 that would raise the productivity of some workers and lower that of others—would be consistent with rising wage inequality but not necessarily raising aggregate labor productivity. Nonetheless, it is rather surprising that whatever shifts in technology led to the rapid growth in inequality between 1980 and 1985 appeared to have no effect on the trend in aggregate productivity.

In comparison to the early 1980s, the late 1990s may turn out to be a better example of a period of rapid technologically driven output growth. As shown in Chart 9, aggregate output growth was considerably above trend in the 1998–2000 period. Moreover, some (but not all) measures of wage inequality show a rise after 1995 or 1996. Some detailed microlevel analyses point to specific technology-related changes in workplace organization that have a significant impact on productivity (see, for example, Bresnahan, Brynjolfsson, and Hitt 2002). In view of the confounding effect of the extraordinary business cycle

CHART 9

Trends in Productivity per Hour, Nonfarm Business Sector



Source: Authors' analysis of Bureau of Labor Statistics data (see footnote 30)

conditions during the late 1990s, however, it may be some time before a definitive interpretation of this period is reached.

Conclusion

What is one to make of recent trends in wage inequality and productivity and the links (or absence of links) to computer-related technology? From the vantage point of an analyst looking at the available data in the mid- to late 1980s, there were many reasons to find skill-biased technological change a plausible explanation for the large increase in inequality that began in the early 1980s. First and foremost, the timing seemed right. During the 1970s, the college/high-school wage gap narrowed. Richard Freeman's 1976 book *The Overeducated American* argued that the U.S. labor market suffered from an oversupply of educated workers. By 1985 the situation had clearly reversed, and education-related wage gaps and other dimensions of wage inequality were on the rise. At the same time, the personal computer was making dramatic inroads into the workplace, the stock market valuation of technology firms was rising, and articles in the business press were expounding the effects of the new technology. Analysts in the late 1980s had no way of knowing that, although computer use would continue to expand over the next decade and the stock market value of technology firms would rise, the increase in wage inequality was largely over.

Viewed from 2002, the rise in wage inequality now appears to have been an episodic event. Of the 17 percent rise in the 90-10 wage gap between 1979 and 1999 for all workers in the OGR wage series (see Chart 2), 13 percentage points (or 76 percent) occurred by 1984, the year that the IBM-AT was introduced. While some of the early rise in inequality may have been due to rapid technological change, we suspect that the increase in the early 1980s is

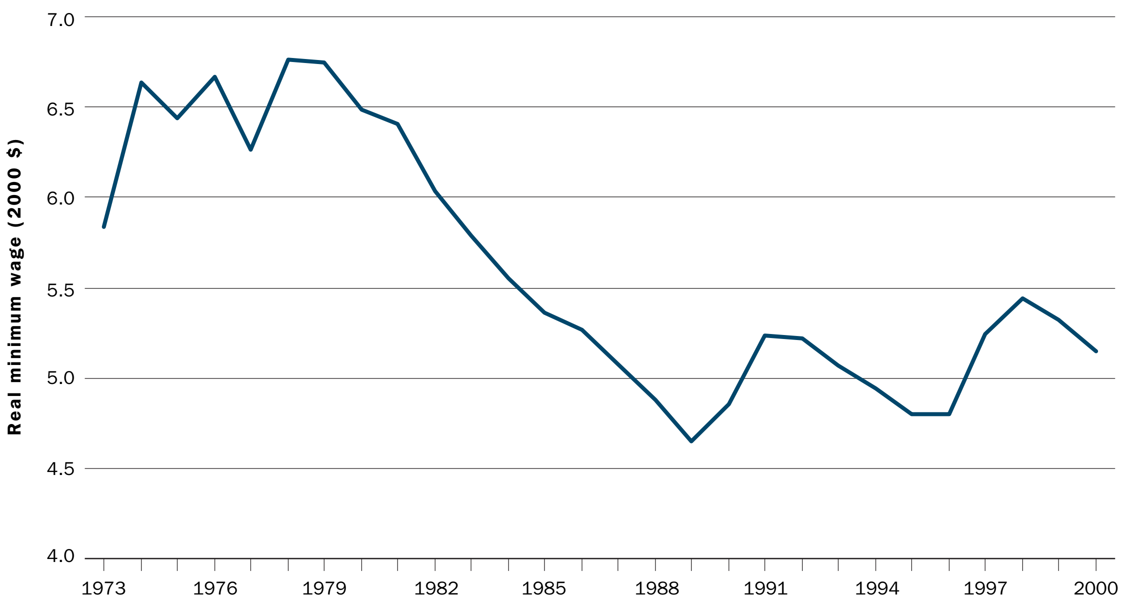
28. To the extent that the measured potential experience profile reflects the relationship between wages and actual experience, for example, such a shift in the labor force participation rates of women would cause a steepening of the wage/potential experience profile.

29. For example, in a 1996 statement Alan Greenspan observed that "the advent of the semiconductor, the microprocessor, the computer, and the satellite . . . has puzzled many of us in that the growth of output as customarily measured has not evidenced a corresponding pickup" (quoted in McGuckin, Stiroh, and van Ark 1997).

30. The productivity series is series PRS85006093, from the U.S. Bureau of Labor Statistics, uploaded December 2001. The fitted trend in the log of output per hour is 0.0262 in the period 1947–75 and 0.0139 in the period 1976–2000.

CHART 10

Real Minimum Wage, 1973–2000



Source: Authors' analysis. See also <www.dol.gov/esa/minwage/chart.htm>.

largely explained by other plausible—albeit relatively mundane—factors. A primary candidate is the fall in the real value of the minimum wage. In 1979 the modal wage for women with a high-school education was $2.90 an hour—the level of the federal minimum wage (DiNardo, Fortin, and Lemieux 1996). Over the next five years the consumer price index rose by 48 percent while the minimum wage increased by only 15 percent, leading to a steep decline in the influence of the minimum wage on the lower tail of the wage distribution. Chart 10 plots the real value of the federal minimum wage between 1973 and 2000. Examination of this figure suggests that it is nearly a mirror image of the inequality series in Chart 2. Indeed, as shown in Chart 11, predictions from a simple regression of the normalized 90-10 wage gap (from the May CPS and OGR data) on the log of the real minimum wage track the actual wage gap very closely. This simple model explains over 90 percent of the variation in the 90-10 wage gap and captures many of the key turning points.

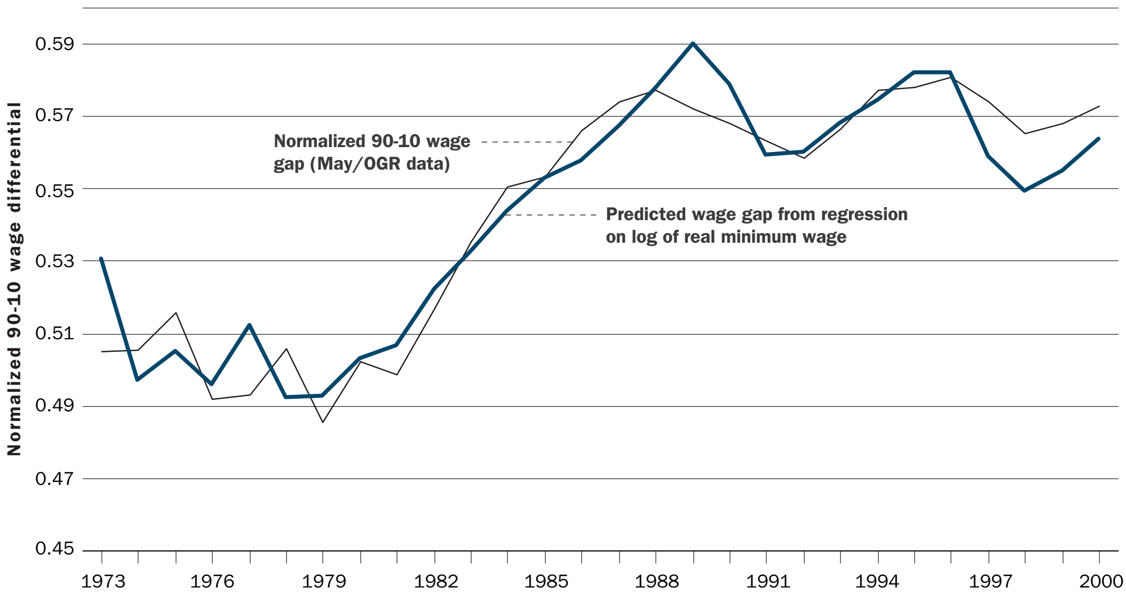
Of course, neither this informal analysis nor the more exhaustive study by Lee (1999) imply that the minimum wage can explain *all* the changes in the wage structure that occurred in the 1980s and 1990s. Indeed, we have documented several important changes that cannot be explained by the minimum wage, including the closing of the gender gap.[31] Nevertheless, we suspect that trends in the minimum wage and other factors such as declining unionization and the reallocation of labor caused by the 1982 recession can help to explain the rapid rise in overall wage inequality in the early 1980s.

Overall, the evidence linking rising wage inequality to skill-biased technological change is surprisingly weak. Moreover, we conjecture that a narrow focus on technology has diverted attention away from many interesting developments in the wage structure that cannot be easily explained by skill-biased technological change. Perhaps the perspective of a new decade will help to open the field of unexplained variance to all players.

31. Lee (1999) presents a detailed cross-state evaluation of the effect of the minimum wage on overall wage inequality and concludes that the fall in the real minimum wage can explain nearly all the rise in aggregate inequality in the 1980s. That the minimum wage explains most of the change in overall inequality, but cannot explain specific changes in the wage structure, is not as puzzling as it might first appear. Fortin and Lemieux (1998, 2000) show that although the 1980s saw very large increases in gender-specific wage inequality, changes in the overall distribution of wages were much smaller. Lee's analysis suggests that these are largely explainable by the minimum wage.

CHART 11

Wage Inequality and the Minimum Wage



Source: Authors' analysis of various May and Outgoing Rotation Group files from monthly Current Population Survey and EPI. See also <www.dol.gov/esa/minwage/chart.htm>.

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Productivity, Computerization, and Skill Change

EDWARD N. WOLFF

Wolff is a professor of economics at New York University. *He thanks the Century Foundation for financial support for the research.*

Robert Solow was, perhaps, the first to point out the anomaly between productivity growth and computerization. Indeed, he quipped that we see computers everywhere except in the productivity statistics. As we shall see, industries that have had the greatest investment in computers (namely, financial services) have ranked among the lowest in terms of conventionally measured productivity growth. Moreover, at least until recently, there has been little evidence of a payoff to computer investment in terms of productivity growth.

However, another recent phenomenon of considerable visibility has been the rapid degree of industrial restructuring among U.S. corporations. This paper argues that standard measures of productivity growth are only one indicator of structural change. There are others, such as changes in direct input and capital coefficients. Changes in occupational mix and the composition of inputs were greater in the 1980s than in the preceding two decades. This pattern coincides with the sharp rise in computerization.

Though most of the literature has focused on the connection between information technology (IT) or information and communications technology (ICT) and productivity, little work has been conducted on the linkage between IT and broader indicators of structural change (with a few exceptions noted below). One purpose of this paper is to help fill this gap. Indeed, this study finds evidence from regression analysis that the degree of computerization has had a statistically significant effect on changes in industry input coefficients and other dimensions of structural change.

Another apparent anomaly arises when we consider the relationship between schooling and skills on the one hand and productivity growth on the other hand. Human capital theory predicts that rising educational attainment and skills will lead to increasing productivity. Considerable policy discussion has also focused on the importance of education and skill upgrading as an ingredient in promoting productivity growth. Yet, as this discussion will show, while overall productivity growth in the United States slowed after 1973, the growth of schooling levels and skills continued unabated. Indeed, college completion rates accelerated after 1970. In the time series data, from 1947 to 1997, there is virtually no correlation between the growth of total factor productivity on the one hand and that of skills or educational attainment on the other. Likewise, on the industry level, sectors with the highest skills—namely services—have had the lowest productivity growth.

This paper will concentrate on the relation of skills, education, and computerization to productivity growth and other indicators of technological change on the industry level. I find no evidence that the growth of educational attainment has any statistically measured effect on industry productivity growth. The growth in cognitive skills, on the other hand, is significantly related to industry productivity growth though the effect is very modest. Moreover, the degree of computerization is not significant. In contrast, computerization has had a statistically significant effect on changes in industry input coefficients.

The paper begins with a review of some of the pertinent literature on the role of skill change and computerization on productivity changes in the U.S. economy. The next two sections introduce the accounting framework and model and present descriptive statistics on postwar productivity trends. Descriptive statistics are also presented for key variables that have shaped the pattern of productivity growth over the postwar period, and multivariate analysis is conducted on the industry level to assess their influence.

This study finds evidence from regression analysis that the degree of computerization has had a statistically significant effect on changes in industry input coefficients and other dimensions of structural change.

Review of Previous Literature

Human capital theory views schooling as an investment in skills and hence as a way of augmenting worker productivity (see, for example, Schultz 1960 and Becker 1975). This line of reasoning leads to growth accounting models in which productivity or output growth is derived as a function of the change in educational attainment. The early studies on this subject showed very powerful effects of educational change on economic growth. Griliches (1970) estimated that the increased educational attainment of the U.S. labor force accounted for one-third of the aggregate technical change between 1940 and 1967. Denison (1979) estimated that about one-fifth of the growth in U.S. national income per person employed (NIPPE) between 1948 and 1973 could be attributed to increases in educational levels of the labor force. Jorgenson and Fraumeni (1993) calculated that improvements in labor quality accounted for one-fourth of U.S. economic growth between 1948 and 1986.

Yet some anomalies have appeared in this line of inquiry. Denison (1983), in his analysis of the productivity slowdown in the United States between 1973 and 1981, reported that the growth in NIPPE fell by 0.2 percentage points whereas increases in educational attainment contributed 0.6 percentage points to the growth in NIPPE. Maddison (1982) reported similar results for other OECD countries for the 1970–79 period. Wolff (2001), using various series on educational attainment, found no statistically significant effect of the growth in mean years of schooling on GDP growth per capita among OECD countries over the 1950–90 period.

A substantial number of studies, perhaps inspired by Solow's quip, have now examined the linkage between computerization or information technology (IT) in general and productivity gains. The evidence is mixed. Most of the earlier studies failed to find any excess returns to IT over and above the fact that these investments are normally in the form of equipment investment. These studies include Franke (1987), who found that the installation of automated teller machines was associated with a lowered real return on equity; Bailey and Gordon (1988), who examined aggregate productivity growth in the United States and found no significant contribution of computerization; Loveman (1988), who reported no productivity gains from IT investment; Parsons, Gotlieb, and Denny (1993), who estimated very low returns on computer investments in Canadian banks; and Berndt and Morrison (1995), who found negative correlations between labor productivity growth and high-tech capital investment in U.S. manufacturing industries. Wolff (1991) found that the insurance industry had a negative rate of total factor productivity growth during the 1948–86 period in the United States even though it ranked fourth among sixty-four industries in terms of computer investment.

The later studies generally tend to be more positive. Both Siegel and Griliches (1992) and Steindel (1992) estimated a positive and significant relationship between computer investment and industry-level productivity growth. Oliner and Sichel (1994) reported a significant contribution of computers to aggregate U.S. output growth. Lichtenberg (1995) estimated firm-level production functions and found an excess return to IT equipment and labor. Siegel (1997), using detailed industry-level manufacturing data for the United States, found that computers are an important source of quality change and that, once correcting output measures for quality change, computerization had a significant positive effect on productivity growth.

Brynjolfsson and Hitt (1996, 1998) found, over the 1987–94 time period, a positive correlation between firm-level productivity growth and IT investment when accompanied by organizational changes. Lehr and Lichtenberg (1998) used data for U.S. federal government agencies for the 1987–92 period and found a significant positive relation between productivity growth and computer intensity. Lehr and Lichtenberg (1999) investigated firm-level data among service industries for the 1977–93 period and also reported evidence that computers, particularly personal computers, contributed positively and significantly to productivity growth. Ten Raa and Wolff (2001), developing a new measure of direct and indirect productivity gains, found that the computer sector was the leading sector in the U.S. economy during the 1980s as a source of economywide productivity growth. They also found very high productivity spillovers between the computer-producing sector and sectors using computers. In their imputation procedure, these large spillovers were attributable to the high rate of productivity growth within the computer industry.

Stiroh (1998) and Jorgenson and Stiroh (1999, 2000) used a growth accounting framework to assess the impact of computers on output growth. Jorgenson and Stiroh (1999) calculated that one-sixth of the 2.4 percent annual growth in output can be attributed to computer outputs compared to about 0 percent for the 1948–73 period. The effect came from capital deepening rather than from enhanced productivity growth. A study by Oliner and Sichel (2000) provides strong evidence for a substantial role of IT in the recent spurt of productivity growth during the second half of the 1990s. Using aggregate time-series data for the United States, they found that both the use of IT in sectors purchasing computers and other forms of information technology and the production of computers appear to have made an important contribution to the speedup of productivity growth in the latter part of the 1990s. Hubbard (2001) investigated how on-board computer adoption affected capacity utilization in the U.S. trucking industry between 1992 and 1997. He found that the use of computers improved communications and resource allocation decisions and led to a 3 percent increase in capacity utilization within the industry.

One other factor that will be used in the data analysis is research and development (R&D). A large literature, beginning with Mansfield (1965), has now almost universally established a positive and significant effect of R&D expenditures on productivity growth (see Griliches 1979 and 1992 and Mohnen 1992 for reviews of the literature).

Modeling Framework

I begin with a standard neoclassical production function f_j for sector j:

$$(1)\quad X_j = Z_j f_j(K_{Cj}, K_{Ej}, K_{Sj}, L_j, N_j, R_j),$$

where X_j is the (gross) output of sector j, K_{Cj} is the input of IT-related capital, K_{Ej} is the input of other machinery and equipment capital goods, K_{Sj} is the input of plant and other structures, L_j is the total labor input, N_j is total intermediate input, R_j is the stock of R&D capital, and Z_j is a (Hicks-neutral) total factor productivity (TFP) index that shifts the production function of sector j over time.[1] For convenience, the time subscript has been suppressed. Moreover, capacity utilization and adjustment costs are ignored. It then follows that

$$(2)\quad d\ln X_j = d\ln Z_j + \varepsilon_{Cj} d\ln K_{Cj} + \varepsilon_{Ej} d\ln K_{Ej} + \varepsilon_{Sj} d\ln K_{Sj} + \varepsilon_{Lj} d\ln L_j + \varepsilon_{Nj} d\ln N_j + \varepsilon_{Rj} d\ln R_j,$$

where ε represents the output elasticity of each input and $d\ln Z_j$ is the rate of Hicks-neutral TFP growth. If the assumption of competitive input markets and constant returns to scale is imposed, it follows that an input's factor share (α_j) will equal its output elasticity. Employing the standard measure of TFP growth, π_j, for sector j,

$$(3)\quad \pi_j \equiv d\ln X_j/dt - \alpha_{Cj} d\ln K_{Cj}/dt - \alpha_{Ej} d\ln K_{Ej}/dt - \alpha_{Sj} d\ln K_{Sj}/dt - \alpha_{Lj} d\ln L_j/dt - \alpha_{Nj} d\ln N_j/dt.$$

It then follows that

$$(4)\quad \pi_j = d\ln Z_j/dt + \alpha_{Rj} d\ln R_j/dt.$$

In particular, in the standard neoclassical model, there is no special place reserved for IT capital in terms of its effect on TFP growth.

As Stiroh (2002) argues, there are several reasons that the standard necoclassical model might be expected to fail in the case of the introduction of a radically new technology that might be captured by IT investment. These include the presence of productivity spillovers from IT, problems of omitted variables, the presence of embodied technological change, measurement error in variables, and reverse causality. If for one of these reasons the output elasticity of IT, ε_{Cj}, exceeds its measured input share, α_{Cj}, say, by u_{Cj}, then

$$(5)\quad \pi_j = d\ln Z_j/dt + \alpha_{Rj} d\ln R_j/dt + u_{Cj} d\ln K_{Cj}/dt.$$

1. This equation is a modified form of the production function used by Stiroh (2002).

In other words, conventionally measured TFP growth, π_j, will be positively correlated with the growth in ICT capital.

A similar argument applies to labor productivity growth, LP, defined as

$$(6)\ LP_j \equiv d\ln X_j/dt - d\ln L_j/dt.$$

If the assumption of competitive input markets and constant returns to scale is again imposed, it follows that

$$(7)\ LP_j = d\ln Z_j/dt + \alpha_{Cj} d\ln k_{Cj}/dt + \alpha_{Ej} d\ln k_{Ej}/dt + \alpha_{Sj} d\ln k_{Sj}/dt + \alpha_{Nj} d\ln n_j/dt + \alpha_{Rj} d\ln R_j/dt,$$

Measures of structural change may provide a more direct and robust test of the effects of computerization on changes in technology than standard measures of productivity growth do.

where lowercase symbols indicate the amount of the input per worker.[2] If for the reasons cited above there is a special productivity "kick" from IT investment, then the estimated coefficient of k_{Cj}/dt should exceeds its factor input share.

However, as indicated in the literature survey in the previous section, very few studies, with the exception of Siegel and Griliches (1992), have found a direct positive correlation between industry TFP growth and IT investment. As a result, this study considers other indicators of the degree of structural change in an industry. These include changes in the occupational composition of employment and in the input and capital composition within an industry. Productivity growth and changes in input composition usually go hand in hand. To illustrate, three new matrices are introduced:

A = forty-five-order matrix of technical interindustry input-output coefficients, where a_{ij} is the amount of input i used per constant dollar of output j.

The technical coefficient (A) matrices are constructed on the basis of current-dollar matrices and sector-specific price deflators. Sectoral price indices for years 1958, 1963, and 1967 were provided by the Brandeis Economic Research Center and those for 1972 and 1977 from the Bureau of Economic Analysis (BEA) worksheets. Deflators for 1982, 1987, 1992, and 1996 are calculated from the Bureau of Labor Statistics' Historical Output Data Series (obtained on computer diskette) on the basis of the current- and constant-dollar series. See the appendix for details on sources and methods and a listing of the forty-five industries.

C = forty-five-order matrix of capital coefficients, where c_{ij} is the net stock of capital of type i (in 1992 dollars) used per constant dollar of output j.

The capital matrix in constant dollars was provided by the BEA (see the appendix for sources) and is based on price deflators for individual components of the capital stock (such as computers, industrial machinery, buildings, etc.).

M = occupation-by-industry employment coefficient matrix, where m_{ij} shows the employment of occupation i in industry j as a share of total employment in industry j.

The employment data are for 267 occupations and 64 industries and were obtained from the decennial Census of Population for the years 1950, 1960, 1970, 1980, and 1990 (see Wolff 1996 for details).

Then, since for any input I in sector j, $\alpha_{Ij} = p_I I_j/p_j X_j$, where p is the price, equation 3 can be rewritten as

$$(8)\ \pi_j = -[\Sigma_i p_i da_{ij} + \Sigma_i p_{i,c} dc_{ij} + \Sigma_i w_i db_{ij}]/p_j,$$

where p_i is the price of intermediate input i, $p_{i,c}$ is the price of capital input i, $b_{ij} = m_{ij}L_j/X_j$ is the total employment of occupation i per unit of output in industry j, and w_i is the wage paid to workers in occupation i. In this formulation, it is clear that measured TFP growth reflects changes in the composition of intermediate inputs, capital inputs, and occupational employment. Using the multiplication rule for derivatives, equation 8 can be rewritten as

$$(9)\ \pi_j = -[\Sigma_i p_i da_{ij} + \Sigma_i p_{i,c} dc_{ij} + \Sigma_i w_i \lambda_j dm_{ij} + \Sigma_i w_i m_{ij} d\lambda_j]/p_j,$$

where $\lambda_j = L_j/X_j$. From equation 5 it follows that, in the circumstances enumerated above, there may be a positive correlation between measures of coefficient changes (such as da_{ij}, dc_{ij}, and dm_{ij}) and IT investment.

Though productivity growth and changes in input composition are algebraically related, there are several reasons they may deviate. First, there are costs of adjustments associated with radical restructuring of technology, so there may be a considerable time lag between the two (see David 1991, for example). Second, while new technology is generally used to lower costs and hence increase measured output per unit of input, new technology might be used for other purposes such as product differentiation or differential pricing. Third, in the case of services in particular, output measurement problems might prevent one from correctly assessing industry productivity growth. This problem could, of course, be partly a consequence of product differentiation and price discrimination. Measures of structural change may therefore provide a more direct and robust test of the effects of computerization on changes in technology than standard measures of productivity growth do, particularly when a radically new technology is introduced and the consequent adjustment period is lengthy.

Finally, the change in average worker skills is included in the production function. There are two possible approaches. Let the effective labor input $E = QL$, where Q is a measure of average worker quality (or skills). Then equation 1 can be rewritten as

$$(10)\quad X_j = Z_j f_j^*(K_{Cj}, K_{Ej}, K_{Sj}, E_j, N_j, R_j).$$

Again assuming competitive input markets and constant returns to scale (to the traditional factors of production) and still using equation 6 to define labor productivity growth, one obtains

$$(11)\quad LP_j = d\ln Z_j/dt + \alpha_{Cj} d\ln k_{Cj}/dt + \alpha_{Ej} d\ln k_{Ej}/dt + \alpha_{Sj} d\ln k_{Sj}/dt + \alpha_{Nj} d\ln n_j/dt + \alpha_{Lj} d\ln Q_j/dt + \alpha_{Rj} d\ln R_j/dt.$$

In this formulation, the rate of labor productivity growth should increase directly with the rate of growth of average worker quality or skills.

The second approach derives from the standard human capital earnings function. From Mincer (1974),

$$\ln w = a_0 + a_1 S,$$

where w is the wage, S is the worker's level of schooling (or skills), and a_0 and a_1 are constants. It follows that

$$(d\ln w)/dt = a_i(dS/dt).$$

By definition, the wage share in sector j is $\alpha_{Lj} = w_j L_j / X_j$. Under the assumptions of competitive input markets and constant returns to scale, $\alpha_{Lj} = \varepsilon_{Lj}$, a constant. Therefore, $X_j/L_j = w_j/\varepsilon_{Lj}$. In this case, effective labor input E is given by the equation: $\mathrm{Ln}E = Q + \ln L$. It follows from equation 6 that

$$(12)\quad LP_j = d\ln Z_j/dt + \alpha_{Cj} d\ln k_{Cj}/dt + \alpha_{Ej} d\ln k_{Ej}/dt + \alpha_{Sj} d\ln k_{Sj}/dt + \alpha_{Nj} d\ln n_j/dt + \alpha_{Lj} dQ_j/dt + \alpha_{Rj} d\ln R_j/dt.$$

In other words, the rate of labor productivity growth should be proportional to the change in the level of average worker quality or skills over the period.

Descriptive Statistics

Technological change. Table 1 shows the annual rate of TFP growth for twelve major sectors over the decades of the 1950s, 1960s, 1970s, and 1980s. The periods are chosen to correspond to the employment by occupation and industry matrices. Factor shares are based on period averages (the Tornqvist-Divisia index). The labor input is based on persons engaged in production (PEP), the number of full-time and part-time employees plus the number of self-employed persons, and the capital input is measured by fixed nonresidential net capital stock (1992 dollars).[3] (See the appendix.)

As shown in Table 1 (and Chart 1), the annual rate of TFP growth for the entire economy fell from 1.4 percent per year in the 1950s to 1 percent per year in the 1960s, plummeted to 0.4 percent per year in the 1970s (the "productivity slowdown" period), but subsequently rose to 0.8 percent in the 1980s.[4] In the goods-producing industries (including communications, transportation, and utilities), there was generally a modest slowdown in TFP productivity growth from the 1950–60 period to the 1960–70 periods, followed by a sharp decline in the

2. Technically, the assumption of constant returns to scale of the traditional factors of production is imposed, so that $\alpha_{Cj} + \alpha_{Ej} + \alpha_{Sj} + \alpha_{Nj} + \alpha_{Lj} = 1$.

3. A second index of TFP growth was also used, with full-time equivalent employees (FTE) as the measure of labor input. Results are very similar on the basis of this measure and are not reported below.

4. In November 1999, the BEA released a major revision of the U.S. national accounts. The new BEA data showed a faster rise in real GDP and hence labor productivity during the 1990s than the older data indicated. One major element of the revision is the treatment of software expenses as a capital good rather than as an intermediate purchase. However, the BEA has not released the corresponding revised capital stock data. As a result, the statistics in this paper are based on the older BEA national accounts data.

TABLE 1

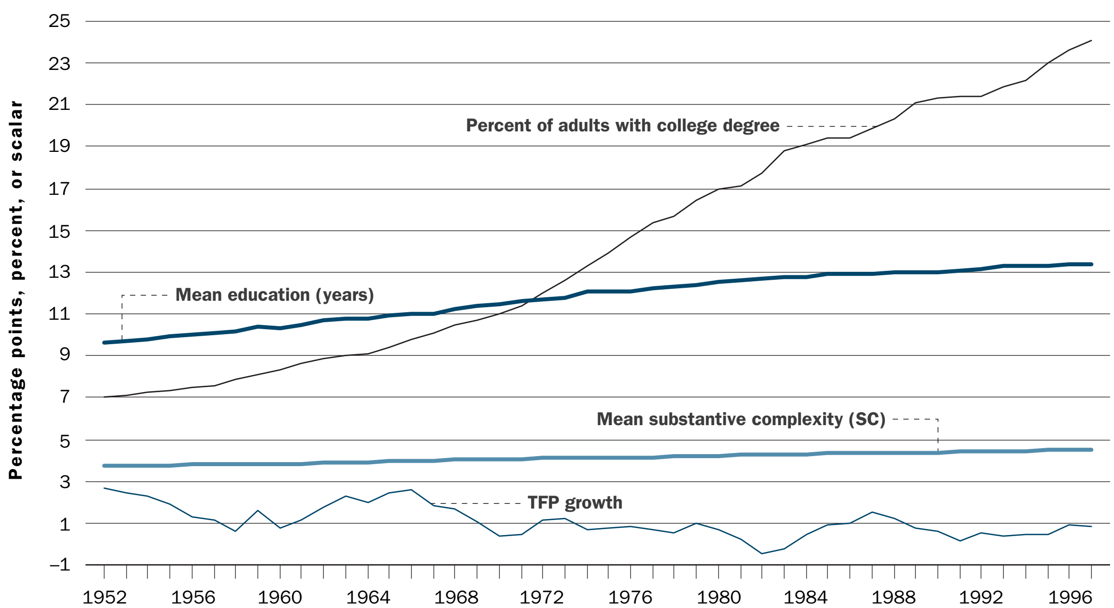
Total Factor Productivity (TFP) Growth by Major Sector, 1950–90

	1950–60	1960–70	1970–80	1980–90	1950–90
A. Goods-producing industries					
Agriculture, forestry, and fisheries	1.54	1.05	–2.33	5.52	1.45
Mining	2.22	3.19	–3.41	3.06	1.27
Construction	4.00	–2.36	–4.48	0.49	–0.59
Manufacturing, durables	1.95	1.72	2.19	3.12	2.25
Manufacturing, nondurables	0.40	1.59	1.07	2.23	1.32
Transportation	1.10	2.97	0.13	0.88	1.27
Communications	2.99	2.55	2.94	1.46	2.49
Electric, gas, and sanitary services	5.35	3.47	2.66	0.62	3.03
B. Service industries					
Wholesale and retail trade	1.08	0.60	–1.01	0.86	0.38
Finance, insurance, and real estate	1.41	0.14	0.37	–1.53	0.10
General services	0.12	–0.05	0.25	–0.35	–0.07
Government and government enterprises	0.59	–0.66	0.15	–0.03	–0.28
Total goods	2.12	1.50	0.25	2.04	1.48
Total services	0.70	0.58	0.58	0.07	0.48
Total economy (GDP)	1.39	0.96	0.38	0.77	0.88

Note: Average annual growth in percentage points.

CHART 1

Annual TFP Growth, Mean Substantive Complexity, Mean Education, and Percent of Adults with a College Education, 1952–97



Note: Annual TFP growth is a five-year running average in percent per year.
Source: See Appendix.

TABLE 2

Dissimilarity Index (DIOCCUP) of the Distribution of Occupational Employment by Major Sector, 1950–90

	1950–60	1960–70	1970–80	1980–90	Average 1950–90
A. Goods-producing industries					
Agriculture, forestry, and fisheries	0.000	0.001	0.001	0.017	0.005
Mining	0.022	0.025	0.020	0.045	0.028
Construction	0.040	0.025	0.005	0.053	0.031
Manufacturing, durables	0.100	0.039	0.014	0.096	0.062
Manufacturing, nondurables	0.077	0.050	0.023	0.088	0.060
Transportation	0.030	0.024	0.014	0.048	0.029
Communications	0.032	0.061	0.043	0.128	0.066
Electric, gas, and sanitary services	0.078	0.169	0.053	0.105	0.101
B. Service industries					
Wholesale and retail trade	0.026	0.019	0.029	0.078	0.038
Finance, insurance, and real estate	0.043	0.117	0.033	0.080	0.068
General services	0.061	0.091	0.029	0.047	0.057
Government and government enterprises	0.046	0.054	0.042	0.045	0.047
Total goods	0.063	0.061	0.014	0.110	0.062
Total services	0.022	0.056	0.026	0.077	0.045
All industries	0.050	0.056	0.019	0.095	0.055

Note: Computations are based on employment by occupation aggregated for each of the major sectors.

1970s (with agriculture, mining, and construction recording negative productivity growth) and then a substantial recovery in the 1980s. The major exceptions are durable manufacturing and communications, whose TFP growth rate rose from the 1960s to the 1970s. TFP growth in the goods-producing industries as a whole averaged 2.1 percent per year in the 1950s, fell to 1.5 percent per year in the 1960s, and then collapsed to 0.3 percent in the 1970s before climbing back to 2 percent per year in the 1980s.

TFP growth has been much lower in the service sector than among goods-producing industries—0.48 percent per year over the 1950–90 period for the former compared to 1.48 percent per year for the latter. The pattern over time is also generally different for the service industries. TFP growth in wholesale and retail trade had a similar pattern to that in goods industries—strong in the 1950–60 period (1.1 percent per year) before falling to 0.6 percent in the 1960s, turning negative in the next decade, and then rebounding to 0.9 percent per year in the 1980s. However, in finance, insurance, and real estate (FIRE) general services, and the government sector, TFP growth dropped from the 1950s to the 1960s, recovered somewhat in the 1970s, and then slipped once again in the 1980s, turning negative in each case. Overall, annual TFP growth among all services fell monotonically between the 1950s and the 1980s, from 0.7 to 0.1 percent.

As noted above, I use three measures of structural change. The first measure is the degree to which the occupational structure shifts over time. For this, I employ an index of similarity. The similarity index for industry j between two time periods 1 and 2 is given by

$$(13)\quad SI^{12} = (\Sigma_i m_{ij}^1 m_{ij}^2)/[\Sigma_i (m_{ij}^1)^2 \Sigma_i (m_{ij}^2)^2]^{1/2}.$$

The index SI is the cosine between the two vectors s^{t1} and s^{t2} and varies from 0 (the two vectors are orthogonal) to 1 (the two vectors are identical). The index of occupational dissimilarity, DI, is defined as

$$(14)\quad \text{DIOCCUP}^{12} = 1 - SI^{12}.$$

Descriptive statistics for DIOCCUP are shown in Table 2. The DIOCCUP index for the total economy, after rising slightly from 0.050 in the 1950s to 0.056 in the 1960s dropped to 0.019 in the 1970s but then surged to 0.095 in the 1980s, its highest level of the four decades. These results confirm anecdotal evidence about the substantial degree of industrial restructuring during the 1980s. Similar patterns are evident for the major sectors as well. In fact, seven of the twelve major sectors

TABLE 3

Dissimilarity Index (DIACOEFF) for Technical Interindustry Coefficients by Major Sector, 1950–90

	1950–60	1960–70	1970–80	1980–90	Average 1950–90
A. Goods-producing industries					
Agriculture, forestry, and fisheries	0.008	0.006	0.004	0.009	0.007
Mining	0.041	0.065	0.070	0.092	0.067
Construction	0.012	0.004	0.028	0.008	0.013
Manufacturing, durables	0.013	0.007	0.009	0.014	0.011
Manufacturing, nondurables	0.022	0.012	0.027	0.025	0.021
Transportation	0.043	0.067	0.016	0.017	0.036
Communications	0.270	0.024	0.051	0.170	0.129
Electric, gas, and sanitary services	0.048	0.087	0.020	0.147	0.075
B. Service industries					
Wholesale and retail trade	0.015	0.049	0.017	0.010	0.023
Finance, insurance, and real estate	0.015	0.033	0.010	0.010	0.017
General services	0.034	0.047	0.066	0.027	0.043
Government and government enterprises	0.054	0.046	0.026	0.061	0.047
Total goods	0.020	0.017	0.024	0.029	0.023
Total services	0.057	0.046	0.043	0.045	0.048
All industries	0.036	0.027	0.030	0.033	0.031

Note: Sectoral figures are based on unweighted averages of industries within the sector.

experienced their most rapid degree of occupational change during the 1980s. The three sectors that experienced the greatest occupational restructuring over the four decades were utilities (0.101), FIRE (0.068), and communications (0.066). Occupational change was particularly low in agriculture (0.005), mining (0.028), transportation (0.029), and construction (0.031).

It is also apparent that the association between the DIOCCUP index and industry TFP growth is quite loose. Though the degree of occupational restructuring has been somewhat greater in the goods-producing industries than in services (average scores of 0.062 and 0.045, respectively, for the 1950–90 period), the difference is not nearly as marked as for TFP growth (annual rates of 1.5 percent and 0.5 percent, respectively, over the same period). Moreover, while FIRE ranks second-highest in terms of occupational change, it is the fourth-lowest in terms of TFP growth. In contrast, while agriculture ranks fourth-highest in terms of TFP growth, it ranks lowest in terms of occupational restructuring. The DIOCCUP index provides a separate and relatively independent dimension of the degree of technological change occurring in an industry.

A second index reflects changes in the technical interindustry coefficients within an industry:

$$(15)\quad \text{DIACOEFF}^{12} = 1 - (\Sigma_i a^1_{ij} a^2_{ij}) / [\Sigma_i (a^1_{ij})^2 \Sigma_i (a^2_{ij})^2]^{1/2}.$$

Figures in Table 3 indicate that the DIACOEFF index for the total economy, after falling from 0.036 in the 1950–60 period to 0.027 in the 1960s, rose to 0.030 in the 1970s and again to 0.033 in the 1980s. Eight of the twelve major sectors also recorded an increase in the degree of change in their interindustry coefficients between the 1960s and the 1980s. The sectors with the greatest interindustry coefficient change over the four decades were communications (0.129), utilities (0.075), and mining (0.067), and the two with the least were agriculture (0.007) and durable manufacturing (0.011).

The correlation between the DIACOEFF index and industry TFP growth is again quite small. While TFP growth was much higher in goods-producing industries than in services, DIACOEFF was higher for services than the goods sector. While agriculture, durable manufacturing, and nondurable manufacturing all ranked high in terms of TFP growth, they were the three lowest in terms of coefficient changes. The DIACOEFF index provides another independent indicator of the degree of industry technological change.

A third index measures the change in capital coefficients within an industry:

TABLE 4

Dissimilarity Index (DIKCOEFF) for Capital Coefficients, 1950–90

	1950–60	1960–70	1970–80	1980–90	Average 1950–90
A. Goods-producing industries					
Agriculture, forestry, and fisheries	0.002	0.000	0.001	0.005	0.002
Mining	0.016	0.008	0.025	0.038	0.022
Construction	0.011	0.016	0.032	0.061	0.030
Manufacturing, durables	0.005	0.007	0.009	0.007	0.007
Manufacturing, nondurables	0.009	0.006	0.006	0.009	0.008
Transportation	0.002	0.009	0.011	0.008	0.007
Communications	0.015	0.028	0.045	0.087	0.044
Electric, gas, and sanitary services	0.003	0.001	0.002	0.003	0.002
B. Service industries					
Wholesale and retail trade	0.045	0.019	0.014	0.024	0.026
Finance, insurance, and real estate	0.020	0.014	0.027	0.043	0.026
General services	0.057	0.033	0.035	0.062	0.047
Total goods	0.008	0.007	0.011	0.014	0.010
Total services (except government)	0.038	0.024	0.029	0.050	0.035
Total economy (except government)	0.020	0.014	0.018	0.028	0.020

Note: Sectoral figures are based on unweighted averages of industries within the sector. Data on investment by type are not available for the government and government enterprises sectors.

$$(16)\quad DIKCOEFF^{12} = 1 - (\Sigma_i c^1_{ij} c^2_{ij}) / [\Sigma_i (c^1_{ij})^2 \Sigma_i (c^2_{ij})^2]^{1/2}.$$

Table 4 shows that the DIKCOEFF index for the total economy, after declining from 0.020 in the 1950s to 0.014 in the 1960s, increased to 0.018 in the 1970s and to 0.028 in the 1980s. DIKCOEFF rose in nine of the eleven major sectors (capital stock by type is not available for the government sector) between the 1960s and the 1980s. General services and communications showed the greatest change in capital coefficients over the 1950–90 period and agriculture and utilities the least. Here, again, while TFP growth was much higher in goods than in service industries, DIKCOEFF was higher for the latter than the former. Moreover, while agriculture, durable manufacturing, and nondurable manufacturing were all among the top industries in terms of TFP growth, they were among the lowest in terms of capital coefficient changes.

Changes in skills and educational attainment. As discussed in the previous two sections, the human capital model predicts a positive relation between changes in average education or average skill levels and productivity growth. Figures on mean years of schooling by industry are derived directly from decennial Census of Population data for 1950, 1960, 1970, 1980, and 1990.

Educational attainment has been widely employed to measure the skills supplied in the workplace. However, the usefulness of schooling measures is limited by such problems as variations in the quality of schooling both over time and among areas, the use of credentials as a screening mechanism, and inflationary trends in credential and certification requirements. Indeed, evidence presented in Wolff (1996) suggests that years of schooling may not closely correspond to the technical skill requirements of the jobs.

As a result, I also make use of the fourth (1977) edition of the *Dictionary of Occupational Titles* (*DOT*) for direct measures of workplace skills. For some 12,000 job titles, it provides a variety of alternative measures of job-skill requirements based upon data collected between 1966 and 1974. It probably provides the best source of detailed measures of skill requirements covering the period 1950 to 1990. Three measures of workplace skills, described below, are developed from this source for each of 267 occupations (see Wolff 1996 for more details).

Substantive complexity (SC). Substantive complexity is a composite measure of skills derived from a factor analytic test of *DOT* variables. It was found to be correlated with general educational development, specific vocational preparation (training time requirements), data (synthesizing, coordinating, analyzing), and three worker aptitudes—intelligence (general learning and reasoning ability), verbal, and numerical.

Interactive skills (IS). Interactive skills can be measured, at least roughly, by the DOT "people" variable, which, on a scale of 0 to 8, identifies whether the job requires mentoring (0), negotiating (1), instructing (2), supervising (3), diverting (4), persuading (5), speaking-signaling (6), serving (7), or taking instructions (8). For comparability with the other measures, this variable is rescaled so that its value ranges from 0 to 10 and reversed so that mentoring is now scored 10 and taking instructions is scored 0.

The human capital model predicts a positive relation between changes in average education or average skill levels and productivity growth.

Motor skills (MS). Motor skills is another DOT factor-based variable. Also scaled from 0 to 10, this measure reflects occupational scores on motor coordination, manual dexterity, and "things"—job requirements that range from setting up machines and precision working to feeding machines and handling materials.

Composite skills (CS). I also introduce a measure of composite skill, CS, which is based on a regression of hourly wages in 1970 on SC, MS, and IS scores across the 267 occupations. The resulting formula is

$$CS = 0.454SC + 0.093MS + 0.028IS$$

SC is the dominant factor in determining relative wages in 1970, followed by MS and then IS.[5]

Average industry skill scores are computed as a weighted average of the skill scores of each occupation, with the occupational employment mix of the industry as weights. Computations are performed for 1950, 1960, 1970, 1980, and 1990 on the basis of consistent occupation by industry employment matrices for each of these years constructed from decennial census data. There are 267 occupations and 64 industries.

Chart 1 provides some evidence on trends in both cognitive skills (substantive complexity), mean education of the workforce, and the percentage of adults with a college degree or more. Cognitive skills do not appear to be closely correlated with TFP growth. The average annual change in the SC index between 1947 and 1973 was .0156 points while TFP growth averaged 1.4 percent per year and .0170 points between 1973 and 1997, when TFP grew at only 0.6 percent per year. Moreover, the growth of college graduates in the adult population was much greater in the later period, averaging 0.45 percentage points per year, than in the earlier period, averaging only 0.28 percentage points per year. Mean schooling, on the other hand, tracks TFP more closely. The average annual change in mean education was 0.096 years over the 1948–73 period and 0.053 years over the 1973–97 period.

There is also very little cross-industry association between skill levels and productivity growth. As Table 5 shows, cognitive skill levels (SC) were, on average, higher in the service sector than the goods sector. In the 1980s, employees in FIRE had the highest average SC score (5.25), followed by general services (4.85), communications (4.74), and the government sector (4.61). On the other hand, the growth in mean SC was somewhat higher in goods industries (0.53 points) than in services (0.43 points) between 1950 and 1990.

The pattern is very similar for the mean education of the workforce. Average schooling was higher in services than in the goods sector and was led by general services (13.7 in 1980–90), followed by FIRE (13.5), government (13.4), and communications (13.3). The change in mean education over the four decades was also larger in the goods sector (3.4 years) than in the service sector (2.6 years).

Investment in OCA. My measure of IT capital is the stock of office, computing, and accounting equipment (OCA) in 1992 dollars, which is provided in the BEA's capital data (see the appendix for sources). These figures are based on the BEA's hedonic price deflator for computers and computer-related equipment. As shown in Table 6 (and Chart 2), investment in OCA per person engaged in production (PEP) grew more than ninefold between the 1950s and the 1990s, from $28 (in 1992 dollars) per PEP to $263. Indeed, by 1997 it had reached $2,178 per worker. By the 1980s, the most OCA-intensive sector by far was FIRE, at $1,211 per employee, followed by utilities ($628), mining ($393), durables manufacturing ($345), and communications ($285). On the whole, the overall service sector has been investing more intensively in computer equipment than the goods sector has, but this pattern was largely due to the very heavy investments made by FIRE. The trade and general service sectors were actually below average in

TABLE 5

Average Skill Level by Period and Major Sector, 1950–90

	1950–60	1960–70	1970–80	1980–90	Change 1950–90
		1. Mean years of education (in years)			
A. Goods-producing industries					
Agriculture, forestry, and fisheries	8.05	9.06	10.45	11.45	4.02
Mining	9.19	10.41	11.56	12.45	4.21
Construction	9.53	10.25	11.21	12.04	3.11
Manufacturing, durables	10.28	11.00	11.67	12.39	2.90
Manufacturing, nondurables	9.75	10.48	11.34	12.13	3.05
Transportation	9.78	10.55	11.44	12.27	3.21
Communications	11.42	11.98	12.62	13.31	2.52
Electric, gas, and sanitary services	10.69	11.19	11.78	12.68	2.79
B. Service industries					
Wholesale and retail trade	10.62	11.18	11.89	12.51	2.33
Finance, insurance, and real estate	11.82	12.40	12.95	13.53	2.29
General services	11.56	12.34	13.08	13.66	2.72
Government and government enterprises	11.50	12.02	12.69	13.37	2.42
Total goods	9.59	10.51	11.43	12.23	3.43
Total services	11.20	11.88	12.62	13.23	2.60
Total economy	10.36	11.25	12.13	12.86	3.23
		2. Mean substantive complexity			
A. Goods-producing industries					
Agriculture, forestry, and fisheries	3.67	3.64	3.61	3.64	0.01
Mining	3.35	3.71	3.98	4.13	1.02
Construction	3.67	4.02	4.16	4.22	0.80
Manufacturing, durables	3.50	3.71	3.84	3.96	0.65
Manufacturing, nondurables	2.98	3.12	3.34	3.49	0.58
Transportation	3.16	3.25	3.35	3.32	0.11
Communications	4.02	4.26	4.51	4.74	0.93
Electric, gas, and sanitary services	3.85	3.87	4.07	4.33	0.56
B. Service industries					
Wholesale and retail trade	3.91	3.84	3.88	3.98	0.04
Finance, insurance, and real estate	4.63	4.96	5.13	5.25	0.90
General services	4.32	4.46	4.73	4.85	0.52
Government and government enterprises	4.24	4.30	4.46	4.61	0.42
Total goods	3.41	3.57	3.73	3.83	0.53
Total services	4.18	4.26	4.44	4.57	0.43
Total economy	3.78	3.94	4.15	4.30	0.62

Note: Figures are weighted averages of individual industries within each major sector.

5. The regression results for 1970 hourly wages (HOURWAGE) are as follows: HOURWAGE = 1.145 + 0.454*SC* + 0.093*MS* + 0.028*IS*, $N = 267$, $R^2 = 0.535$(4.78) (12.1) (2.37) (0.70), with t-ratios shown in parentheses. See the *DOT*, chapter 3, section 2, for more discussion and analysis and for corresponding regression results for other years.

TABLE 6

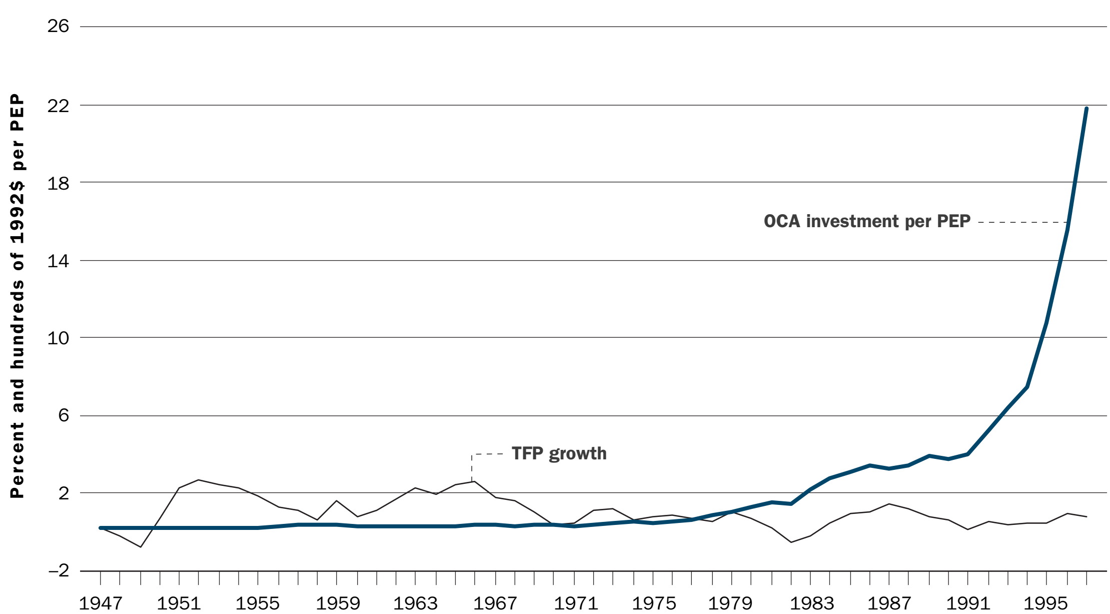
Annual Investment in Office, Computing, and Accounting Equipment (OCA) per Persons Engaged in Production (PEP), 1950–90 (1992$, Period Averages)

	1950–60	1960–70	1970–80	1980–90	Ratio of 1980–90 to 1950–60
A. Goods-producing industries					
Agriculture, forestry, and fisheries	0.1	0.3	2.1	4.9	67.4
Mining	14.3	28.6	53.3	392.9	27.5
Construction	6.8	6.9	5.8	7.7	1.1
Manufacturing, durables	24.5	21.5	30.2	119.9	4.9
Manufacturing, nondurables	49.2	54.5	98.3	345.3	7.0
Transportation	43.7	36.5	29.6	72.7	1.7
Communications	49.1	43.6	51.1	285.2	5.8
Electric, gas, and sanitary services	47.2	41.8	54.5	628.3	13.3
B. Service industries					
Wholesale and retail trade	14.0	20.3	42.5	279.8	20.0
Finance, insurance, and real estate	140.0	162.7	339.4	1211.0	8.7
General services	22.9	23.4	23.0	148.0	6.5
Total goods	26.4	27.7	42.0	162.1	6.1
Total services (except government)	30.4	37.8	70.0	329.4	10.8
Total economy (except government)	28.2	32.6	57.0	262.7	9.3

Note: Data on investment in OCA are not available for the government and government enterprises sectors.

CHART 2

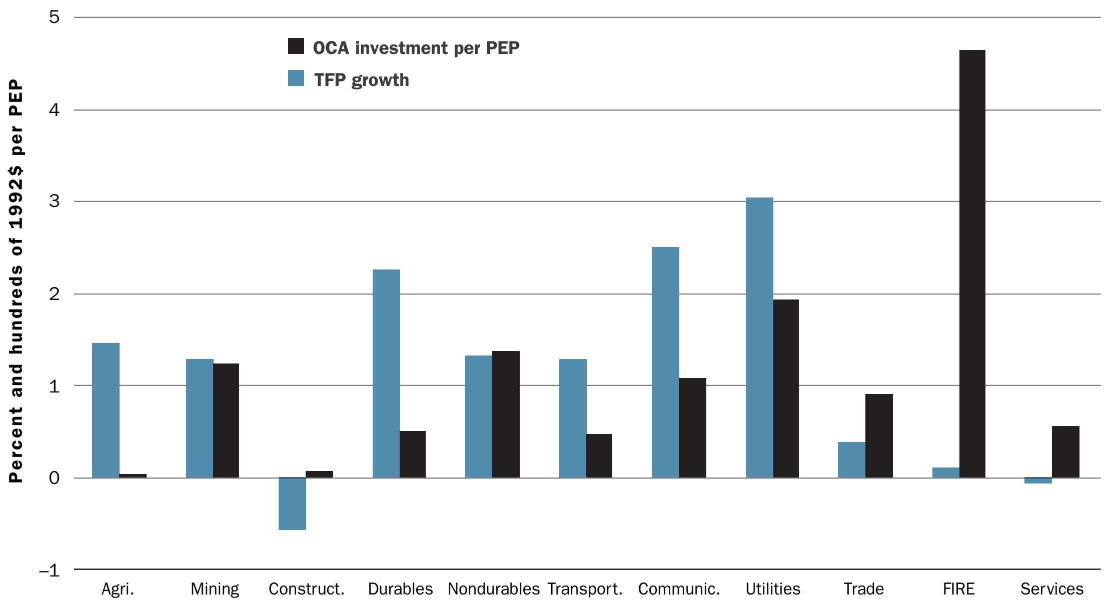
Annual TFP Growth and OCA Investment per Worker, 1947–97



Note: Annual TFP growth is a five-year running average in percent per year. OCA investment is in hundreds of 1992 dollars per PEP.
Source: See Appendix.

CHART 3

TFP Growth and OCA Investment per Worker, 1950–90



Note: Annual TFP growth is a five-year running average in percent per year. OCA investment is in hundreds of 1992 dollars per PEP.
Source: See Appendix.

terms of OCA investment per PEP. Total investment in equipment, machinery, and instruments (including OCA) per PEP was more than fourteen times greater than OCA investment even in the 1980s though by 1997 it accounted for almost exactly one-third of total equipment investment.

On the surface, at least, there does not appear to be much relation between OCA intensity and TFP growth. While investment in OCA per worker rose almost continuously over the postwar period, TFP growth tracked downward, at least until the early 1980s (see Chart 2). Moreover, the sector with the highest amount of OCA investment per worker, FIRE, averaged close to zero in terms of TFP growth over the postwar period (see Chart 3).

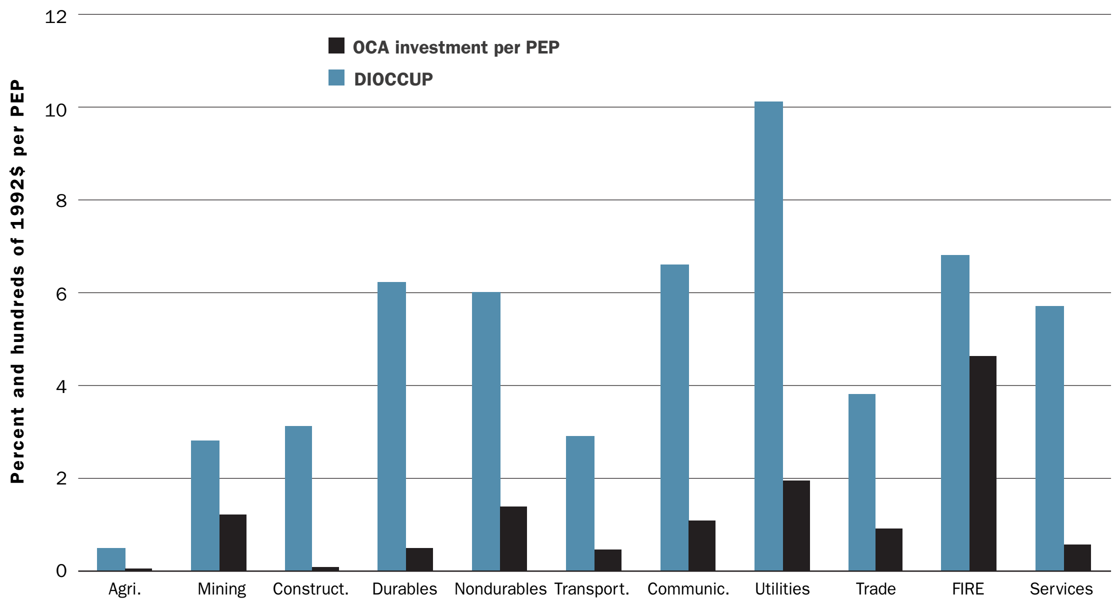
On the other hand, OCA investment seems to line up well with measures of structural change. As shown in Chart 4, the sectors with two highest rates of investment in OCA per PEP over the 1950–90 period are FIRE and utilities, which also rank in the top two in terms of the average value of DIOCCUP over the same period. The sector with the lowest investment in OCA per worker is agriculture, which also ranks lowest in terms of DIOCCUP. Utilities ranks highest in terms of DIACOEFF over the 1950–90 period and second-highest in terms of OCA investment per employee while agriculture ranks lowest in both dimensions (see Chart 5). The association is not quite as tight between OCA investment and DIKCOEFF (see Chart 6). However, here again agriculture ranks lowest in both dimensions.

R&D. As shown in Chart 7, the ratio of R&D expenditures to total GDP has remained relatively constant over time, at least in comparison to the wide fluctuations in TFP growth. It averaged 2 percent in the 1960s, fell to 1.5 percent in the 1970s, recovered to 1.9 percent in the 1980s, and remained at this level in the 1990–97 period. The pattern is very similar for individual industries, with the notable exceptions of industrial machinery (including OCA) and instruments, which show a continuous rise over the three periods. The ratio of R&D to sales was considerably higher—by almost a factor of three—in durable manufacturing than in nondurables. In the 1980–90 period, it ranged from a low of 0.4 percent in food products to a high of 18.3 percent in other transportation (including aircraft). The other major R&D-intensive industries, in rank order, are instruments, electric and electronic equipment, industrial machinery, chemicals, and motor vehicles.

An alternative indicator of R&D activity is the number of full-time-equivalent scientists and engineers engaged in R&D per 1,000 full-time-equivalent employees. Like the ratio of R&D expenditures to GDP, this series shows a drop between the 1960s and

CHART 4

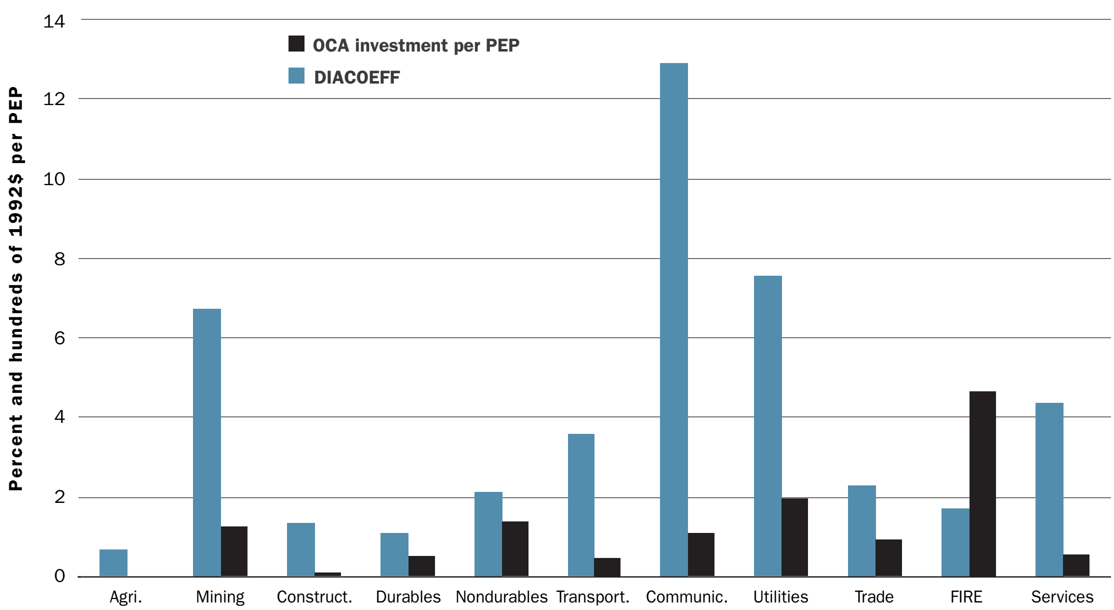
DIOCCUP and OCA Investment per Worker, 1950–90



Note: DIOCCUP is an average for the period in percent. OCA investment is in hundreds of 1992 dollars per PEP.
Source: See Appendix.

CHART 5

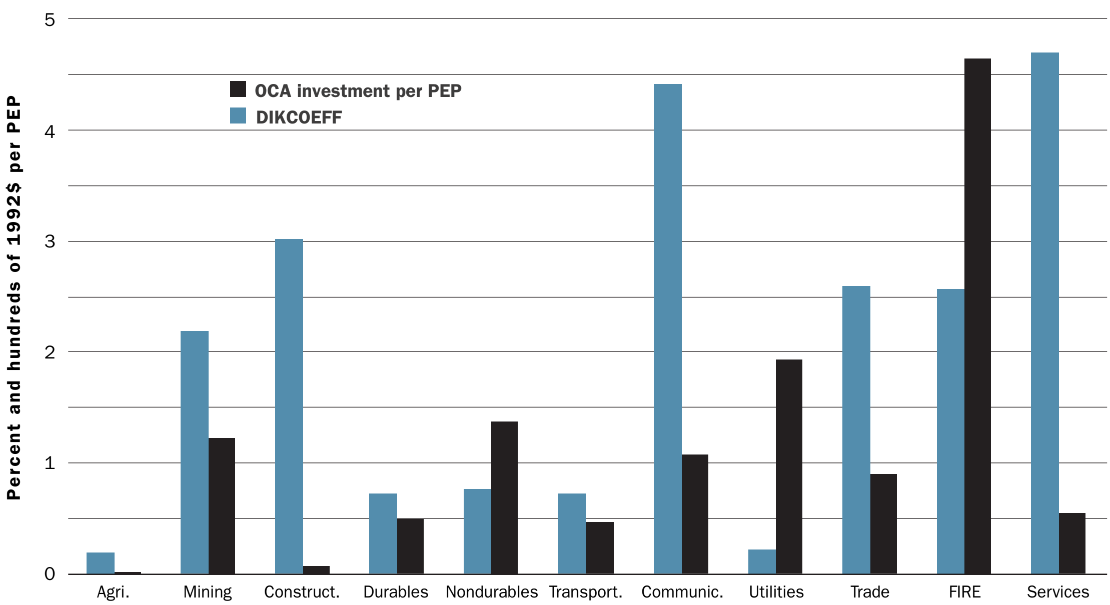
DIACOEFF and OCA Investment per Worker, 1950–90



Note: DIACOEFF is an average for the period in percent. OCA investment is in hundreds of 1992 dollars per PEP.
Source: See Appendix.

CHART 6

DIKCOEFF and OCA Investment per Worker, 1950–90



Note: DIKCOEFF is an average for the period in percent. OCA investment is in hundreds of 1992 dollars per PEP.
Source: See Appendix.

1970s, from 5.4 to 4.8, and a recovery in the 1980s to 6.4 (see Chart 7). However, it shows a further increase to 7.3 in the 1990–96 period. This indicator also gives a very similar industry ranking. The leading industries in the 1980s, in rank order, are other transportation, chemicals, electric and electronic equipment, industrial machinery, instruments, and motor vehicles.

R&D expenditures does a much better job in lining up with TFP growth than either OCA or equipment investment. Both R&D intensity and TFP growth fell from the 1960s to the 1970s and then recovered in the 1980s. Moreover, there is a strong cross-industry correlation between TFP growth and R&D intensity—for example, both R&D intensity and TFP growth are higher in durable manufacturing than in nondurable manufacturing.

Regression Analysis

In the first regression, the dependent variable is the rate of industry TFP growth. The independent variables are R&D expenditures as a percent of net sales and the growth in the stock of OCA capital. The statistical technique is based on pooled cross-section time-series regressions on industries and for the decades that correspond with the decennial census data. The sample consists of forty-five industries and three time periods (1960–70, 1970–80, and 1980–90).[6] The estimating equation is

$$(17)\quad TFPGRTH_j = \beta_0 + \beta_1 RDSALES_j + \beta_2 OCAGRTH_j + vj,$$

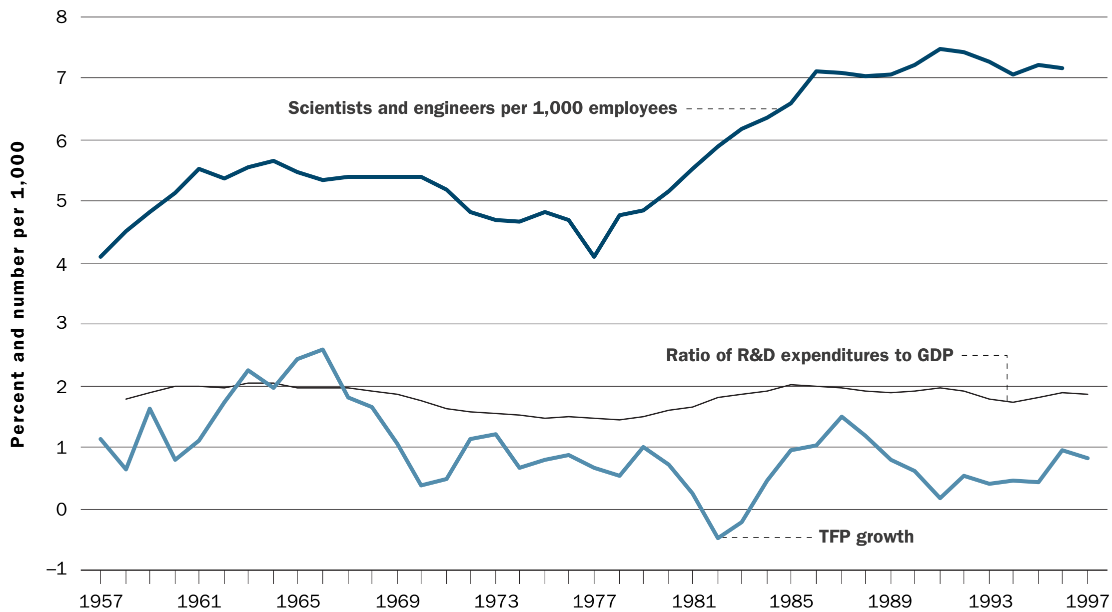
where $TFPGRTH_j$ is the rate of TFP growth in sector j, $RDSALES_j$ is the ratio of R&D expenditures to net sales in sector j, OCAGRTH is the rate of growth of the stock of OCA capital, v_j is a stochastic error term, and the time subscript has been suppressed for notational convenience. It is assumed that the v_{jt} are independently distributed but may not be identically distributed. The regression results reported below use the White procedure for a heteroscedasticity-consistent covariance matrix.

From equation 4 it follows that the constant β_0 is the pure rate of (Hicks-neutral) technological progress. From Griliches (1980) and Mansfield (1980), the coefficient of RDSALES is interpreted as the rate of return of R&D under the assumption

6. The 1950–60 period cannot be included in the regression analysis because the R&D series begins fully only in 1958.

CHART 7

DIKCOEFF and OCA Investment per Worker, 1950–90



Note: DIKCOEFF is an average for the period in percent. OCA investment is in hundreds of 1992 dollars per PEP.
Source: See Appendix.

that the (average) rate of return to R&D is equalized across sectors.[7] Time dummies for the periods 1970–80 and 1980–90 are introduced to allow for period-specific effects on productivity growth not attributable to R&D or OCA investment. A dummy variable identifying the ten service industries is also included to partially control for measurement problems in service sector output.

Basic Regression Results

Regression results for the full sample are shown in columns 1 and 2 of Table 7. The constant term ranges from 0.015 to 0.016. These estimates are comparable to previous estimates of the Hicks-neutral rate of technological change (see Griliches 1979, for example). The coefficient of the ratio of R&D expenditures to net sales is significant at the 5 percent level. The estimated rate of return to R&D ranges from 0.20 to 0.21. These estimates are about average compared to previous work on the subject (see Mohnen 1992, for example, for a review of previous studies).[8]

The coefficient of the growth of OCA is negative but not statistically significant. The same result holds for two alternative measures of IT, the growth in the stock of computers and the stock of OCA plus communications equipment (OCACM). As noted above, these specifications really measure the excess returns to computer investment over and above that to capital in general since TFP growth already controls for the growth of total capital stock per worker. The coefficient of the dummy variable for service industries is significant at the 1 percent level; its value is –0.017. The coefficient of the dummy variable for the 1970–80 period is negative (significant in one of the two cases), and that for the 1980–90 period is positive (but not significant).

Because of difficulties in measuring output in many service industries, regressions were also performed separately for the thirty-one goods-producing industries (see the appendix table).[9] The coefficient values and significance levels of the constant term, R&D intensity, the dummy variable for services, and the two time period dummy variables are strikingly similar to those for the all-industry regressions (see specifications 3 and 4 of Table 7). The coefficient of the growth in computer stock remains negative but insignificant (specification 4).[10]

The next two regressions, focus on the "computer age," the period from 1970 onward. Does the effect of computerization on productivity growth now show up for this restricted sample? The answer is still negative, as shown in specifications 5 and 6 of Table 7. The coefficients of the other two computerization variables, the rate of growth in the stock of computers and that of OCACM are also insignificant

TABLE 7

Cross-Industry Regressions of Industry TFP Growth (TFPGRTH) on R&D Intensity and OCA Investment

Independent variables	Specification (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.015**	0.016**	0.014*	0.014**	0.011	0.020	0.010	0.005
	(3.45)	(3.59)	(2.59)	(2.63)	(1.38)	(1.53)	(1.24)	(0.35)
Ratio of R&D expenditures to sales	0.203*	0.212*	0.199#	0.205#	0.338*	0.348#	0.171*	0.131#
	(2.17)	(2.24)	(1.89)	(1.93)	(2.28)	(2.00)	(2.26)	(1.86)
Annual growth in OCA		–0.039		–0.024	–0.053	–0.102	–0.060	–0.016
		(1.36)		(0.62)	(1.27)	(1.21)	(1.29)	(0.19)
Dummy variable for services	–0.017**	–0.017**			–0.018*		–0.032**	–0.023*
	(3.47)	(3.34)			(2.47)		(3.08)	(2.10)
Dummy variable for 1970–80	–0.010#	–0.006	–0.012#	–0.009				
	(1.89)	(0.95)	(1.74)	(1.05)				
Dummy variable for 1980–90 (or 1987–97)	0.003	0.007	0.009	0.011	0.012#	0.008	0.005	
	(0.59)	(1.13)	(1.22)	(1.37)	(1.95)	(0.80)	(0.81)	
R^2	0.195	0.205	0.127	0.131	0.216	0.145	0.232	0.187
Adjusted R^2	0.171	0.174	0.098	0.092	0.178	0.078	0.201	0.129
Standard error	0.0249	0.0251	0.0280	0.0281	0.0286	0.0289	0.0267	0.0292
Sample size	132	132	93	93	88	42	88	44
Sample	All	All	Goods	Goods	All	Goods	All	All
Period	1960–90	1960–90	1960–90	1960–90	1970–90	1970–90	1977–97	1987–97

Note: Significance levels: #, 10%; *, 5%; **, 1%. The full sample consists of pooled cross-section time-series data, with observations on each of 44 industries in 1960–70, 1970–80, and 1980–90 or in 1977–87 and 1987–97 (sector 45, public administration, is excluded because of a lack of appropriate capital stock data). The goods sample consists of 31 industries (industries 1 to 31 in the Appendix table). The coefficients are estimated using the White procedure for a heteroscedasticity-consistent covariance matrix. The absolute value of the *t*-statistic is in parentheses below the coefficient. See the Appendix for sources and methods.

(results not shown). R&D intensity remains significant in these regressions, and the estimated return to R&D is higher, between 34 and 35 percent. The same results for computerization (and R&D investment) are found when the sample is further restricted to the 1980–90 period.

Specification 7 in Table 7 is based on a pooled sample of observations for the 1977–87 and 1987–97 periods, while specification 8 is restricted to the 1987–97 period. As before, the coefficient of the growth of OCA per worker is negative but not significant. Likewise, the coefficients of the rate of growth in the stock of OCACM per employee and the rate of growth of computers per employee are insignificant (results not shown). In these regressions, the coefficient of R&D intensity remains significant but is somewhat lower (a range of 0.13 to 0.17) while the coefficient of the service dummy variable also stays significant but is higher in absolute value (a range of –0.23 to –0.032).

Regression results with worker skills. Table 8 shows the regression results for the various measures of worker skills and for the two alternative formulations. Following equations 11 and 12, I use labor productivity growth as the dependent variable. The first specification does not include skill

7. The proof is that RDSALES = dR/X. From equations 2 and 4 it follows that $\pi = \varepsilon_R(dR/R) = \varepsilon_R(dR/X)(X/R) = (\varepsilon_R X/R)(dR/X)$. Therefore, $\beta_1 = (\varepsilon_R X/R) = (dX/X)(X/R)/(dR/R) = dX/dR$. The term dX/dR is the marginal productivity of R&D capital, which is equivalent to the rate of return to R&D.
8. The coefficient of the number of full-time-equivalent scientists and engineers engaged in R&D per employee is also significant in every case, typically at the 1 percent level. The tables present results using R&D expenditures because it is more conventional.
9. Since output measurement problems are less likely to affect transportation, communications, and utilities, they are classified as goods-producing industries here.
10. Results are again similar when the sample of industries is further restricted to the twenty manufacturing industries (results not shown).

TABLE 8

Cross-Industry Regressions of Industry Labor Productivity Growth on R&D Intensity, Capital Investment, and Skill Change, 1960–90

Independent variables	Specification (1)	(2)	(3)	(4)	(5)	(6)	(7)
Constant	0.017**	0.033	0.031**	0.030*	0.038*	0.017**	0.014#
	(2.96)	(1.47)	(3.23)	(3.39)	(2.00)	(2.81)	(1.74)
Ratio of R&D expenditures to sales	0.164#	0.182#	0.174#	0.184#	0.178#	0.174#	0.170#
	(1.73)	(1.86)	(1.84)	(1.95)	(1.86)	(1.77)	(1.77)
Growth in OCA per worker	–0.006						
	(0.20)						
Growth in total capital less OCA per worker	0.262*						
	(2.50)						
Growth in total capital per worker		0.235*	0.237*	0.239*	0.252*	0.244*	0.251*
		(2.27)	(2.31)	(2.34)	(2.45)	(2.31)	(2.43)
Growth in substantive complexity (SC)		0.181	0.125#				
		(1.19)	(1.78)				
Growth in interactive skills (IS)		–0.055					
		(0.44)					
Growth in motor skills (MS)		–0.015					
		(0.09)					
Growth in composite skills (CS)				0.202#			
				(1.89)			
Growth in mean education					0.110		
					(1.14)		
Change in substantive complexity (SC)						0.224	
						(0.90)	
Change in interactive skills (IS)						–0.346	
						(1.04)	
Change in motor skills (MS)						0.006	
						(0.02)	
Change in mean education							0.056
							(0.66)
Dummy variable for services	–0.014**	–0.013#	–0.011*	–0.011*	–0.012*	–0.015**	–0.013*
	(2.66)	(1.93)	(2.14)	(2.05)	(2.13)	(2.92)	(2.47)
Dummy variable for 1970–80	–0.009#	–0.009	–0.009	–0.009*	–0.012*	–0.009	–0.012*
	(1.47)	(1.60)	(1.65)	(1.59)	(2.12)	(1.59)	(1.98)
Dummy variable for 1980–90	0.005	0.006	0.006	0.006	0.009	0.008	0.004
	(0.82)	(0.96)	(1.00)	(1.08)	(0.99)	(1.23)	(0.77)
R^2	0.217	0.236	0.234	0.237	0.223	0.226	0.218
Adjusted R^2	0.179	0.186	0.197	0.200	0.186	0.176	0.180
Standard error	0.0252	0.0251	0.0249	0.0249	0.0251	0.0253	0.0252
Sample size	132	132	132	132	132	132	132

Note: Significance levels: #, 10%; *, 5%; **, 1%.The sample consists of pooled cross-section time-series data, with observations on each of 44 industries in 1960–70, 1970–80, and 1980–90 (sector 45, public administration, is excluded because of a lack of appropriate capital stock data).The coefficients are estimated using the White procedure for a heteroscedasticity-consistent covariance matrix. The absolute value of the *t*-statistic is in parentheses below the coefficient. See the Appendix for sources and methods.

change but splits total capital into OCA and other capital. The coefficient of the growth of OCA per worker is virtually zero, and the t-statistic is close to zero. This result provides further corroboration of a lack of a special effect of OCA investment on productivity growth.

In the second specification, I include the annual change of the three measures of workplace skill: substantive complexity (SC), interactive skills (IS), and motor skills (MS). I also include the growth of total capital per worker. None of the skill variables is statistically significant in this regression. The coefficients of the growth of IS and MS are, in fact, negative. However, when the growth in cognitive skills is included by itself, its coefficient becomes marginally significant (at the 10 percent level). Its elasticity is 0.13. The growth in the composite skill index (CS) is also significant at the 10 percent level (with a higher t-ratio) and its elasticity is 0.20 (specification 4). The best fit (highest adjusted R^2) occurs with the use of the CS variable. The coefficient of the growth in mean schooling is also positive, with an elasticity of 0.11, but not statistically significant (specification 5).

Estimated coefficients for the change in mean skills and mean schooling are not as significant as those for the corresponding growth rates (specifications 6 and 7). None of the coefficients is even close to significance. These results suggest that the labor productivity growth is more closely related to the growth in worker schools rather than to their absolute change. This set of results remains robust among alternative samples—goods-producing industries only and for the 1970–90 period.[11]

In the set of regressions shown in Table 8, R&D intensity is significant at the 10 percent level and its estimated value is somewhat lower than in the corresponding TFP regressions (Table 7). The coefficient of the dummy variable for services is also slightly lower (in absolute value) than in the TFP regressions. The coefficient of the growth of total capital per worker is in the range of 0.24 to 0.25, somewhat lower than its income share, and is significant at the 5 percent level in all cases.

As discussed in the introduction, Brynjolfsson and Hitt (1996, 1998) found a positive correlation between firm-level productivity growth and IT investment when the introduction of IT was accompanied by organizational changes. This finding suggests that interaction effects may exist between OCA investment and changes in occupational composition. This was investigated by adding an interaction term between the growth of OCA per worker and DIOCCUP to the labor productivity regression equation derived from equation 11. The regression was estimated for the full sample of industries over both the 1960–90 and the 1970–90 periods and for goods industries only over the two sets of periods. The coefficient of the interaction term is statistically insignificant in all cases and actually negative in about half the cases.[12]

Computerization is found to be strongly linked to occupational restructuring and changes in material usage and weakly linked to changes in the composition of capital.

Other indicators of technological activity. In the last set of regressions, shown in Table 9, measures of structural change are used as dependent variables. As before, the statistical technique is based on pooled cross-section time-series regressions on industries and for the decades that correspond with the decennial Census data. The sample consists of forty-four industries and two time periods (1970–80 and 1980–90).[13] The basic estimating equation is of the same form as equation 17, with R&D intensity and the growth of OCA stock as independent variables. Dummy variables are also included for the service sector and the 1970–80 period. Moreover, following equation 11, I also use the growth of OCA per worker and OCA investment per worker as independent variables in place of the growth of total OCA stock.

The first of the dependent variables is the change in occupational composition (DIOCCUP). In contrast to the TFP regressions, the coefficient of investment in OCA per worker is positive and significant at the

11. Results remain almost unchanged when an alternative measure of labor productivity growth, based on full-time-equivalent employees (FTE) instead of persons engaged in production, is used as the dependent variable.

12. Regressions were also estimated with interaction terms between the growth of OCA per worker and the growth or change in SC < CS and mean education. None of these interaction terms was found to be statistically significant.

13. The 1950–60 and 1960–70 periods are not included in the regression analysis because OCA investment was very small during these periods. The government sector, moreover, cannot be included because of a lack of data on OCA investment.

TABLE 9

Cross-Industry Regressions of Indicators of Structural Change on Computer Investment

Independent variables	Dependent variable DIOCCUP	DIOCCUP	DIACOEFF	DIACOEFF	DIKCOEFF	DIKCOEFF
Constant	0.048**	0.055**	0.001	–0.02*	0.016**	0.008
	7.29	(8.00)	(0.13)	(2.24)	(2.98)	(1.02)
Ratio of R&D expenditures to sales	0.251	0.214	0.136	0.309	0.206	0.129
	(1.10)	(0.97)	(0.59)	(1.57)	(1.17)	(0.71)
Investment in OCA per worker	0.060**	0.048*	0.043**	0.024**		
	(3.07)	(2.23)	(5.24)	(2.98)		
Initial level of OCA per worker					0.032#	0.031#
					(1.81)	(1.66)
Dummy variable for services		0.008		0.017		0.026**
		(0.08)		(1.51)		(2.83)
Dummy variable for 1970–980		–0.021*		-0.001		–0.007
		(2.30)		(0.12)		(0.89)
R^2	0.112	0.145	0.250	0.271	0.135	0.165
Adjusted R^2	0.091	0.104	0.223	0.227	0.104	0.114
Standard error	0.0470	0.0457	0.0429	0.0410	0.0339	0.0341
Sample size	88	88	88	88	88	88
Industries	All	All	All	All	All	All

Note: Significance level: #, 10%; *, 5%; **, 1%. DIOCCUP is dissimilarity index for occupational coefficients; DIACOEFF is dissimilarity index for technical interindustry coefficients; DIKCOEFF is dissimilarity index for capital coefficients. The sample consists of pooled cross-section time-series data, with observations on each of forty-four industries (excluding the government sector) in 1970–80 and 1980–90. The coefficients are estimated using the White procedure for a heteroscedasticity-consistent covariance matrix. The absolute value of the *t*-statistic is shown in parentheses below the coefficient estimate.

1 percent level in the regression without the service and time period dummy variables and positive and significant at the 5 percent level when the dummy variables are included. The coefficients of the alternative computerization measures, the growth in OCA per employee, investment in OCACM per worker, and the rate of growth in the stock of OCACM per employee are also significant at the 1 or 5 percent level (results not shown). However, the best fit is provided by investment in OCA per worker. The results also show that R&D intensity is not a significant explanatory factor in accounting for changes in occupational composition, nor is the dummy variable for services. However, the time period dummy variable is significant at the 5 percent level.[14]

The second variable is DIACOEFF, a measure of the degree of change in interindustry technical coefficients. In this case too, computerization is significant at the 1 percent level with the predicted positive coefficient. The best fit is provided by investment in OCA per worker. The coefficient of R&D intensity is positive but not statistically significant, as is the coefficient of the dummy variable for services. The coefficient of the time dummy variable is virtually zero.

The third index of structural change is DIKCOEFF, a measure of how much the composition of capital has changed over the period. In this case, it is not possible to use investment in OCA as an independent variable since, by construction, it will be correlated with changes in the capital coefficients. Instead, I use the initial level of OCA per worker. The computerization variable has the predicted positive sign and is significant, though only at the 10 percent level. The coefficient of R&D is positive but insignificant. However, the dummy variable for services is positive and significant at the 1 percent level. The coefficient of the dummy variable for 1970–80 is negative but not significant.

In sum, computerization is found to be strongly linked to occupational restructuring and changes in material usage and weakly linked to changes in the composition of capital. For the first result, it might be appropriate to look at the construction of industry OCA by the BEA. The allocation of investment in OCA is based partly on the occupational composition of an industry. As a result, a spurious correlation may be introduced between industry-level OCA investment and the skill mix of an industry. The cross-industry correlation between OCA per worker and the mean SC level is 0.48 in 1970, 0.39 in 1980, and 0.56 in 1990 while that between OCA per worker and the mean schooling level of an industry is 0.46 in 1970, 0.29 in 1980, and 0.37 in 1990.

However, there is no indication that this allocation procedure should affect the change in occupational composition and hence introduce a spurious correlation between OCA investment and the DIOCCUP variable. Moreover, the time-series evidence shows a marked acceleration in the degree of occupational change between the 1970s and 1980s, when OCA investment rose substantially. Regressions of the change in occupational composition (DIOCCUP) on both the growth of equipment per worker and the growth of total capital per worker fail to yield significant coefficients. As a result, we can surmise that this finding is on solid ground.

Conclusion and Interpretation of Results

Three sets of findings emerge from the regression analysis. First, the regression results provide some modest evidence that skill growth is positively linked with productivity growth. The coefficients of the growth in both cognitive skills (SC) and the composite skill (CS) index are marginally significant (at the 10 percent level). The effects are not large—elasticities of 0.125 and 0.202, respectively. Between 1947 and 1997, cognitive skills have grown at an average annual rate of 0.41 percent, and composite skills by 0.33 percent. The growth of cognitive skills over this period would have added 0.05 percentage points to the growth of annual labor productivity, while the growth of composite skills would have added 0.07 percentage points. On the other hand, the coefficient of the growth of the mean education of the workforce, while positive, is not statistically significant. Its estimated elasticity is 0.110. Since mean education grew, on average, by 0.69 percent per year over the 1947–97 period, its growth would have added 0.07 percentage points to annual labor productivity growth.

These findings appear to be inconsistent with growth accounting models, which have attributed a substantial portion of the growth in U.S. productivity to increases in schooling levels. The conflict stems from methodological differences in the two techniques. Growth accounting simply assigns to schooling (or measures of labor quality) a (positive) role in productivity growth based on the share of labor in total income. In contrast, in regression analysis an estimation procedure is used to determine whether a variable such as education is a significant factor in productivity growth.

The findings on the role of education in productivity growth also appear to be at variance with the standard human capital model. There are several possible reasons. First, the causal relation between productivity and schooling may be the reverse of what is normally assumed. In particular, as per capita income rises within a country, schooling opportunities increase, and more and more students may seek a college education (see Griliches 1996 for a discussion of the endogeneity of education). Second, the skills acquired in formal education, particularly at the university level, may not be relevant to the workplace. Rather, higher education may perform a screening function, and a university degree may serve employers mainly as a signal of potential productive ability (see Arrow 1973 or Spence 1973). As enrollment rates rise, screening or educational credentials may gain in importance, and a higher proportion of university graduates may become overeducated relative to the actual skills required in the workplace.

A third possibility is that university education may be associated with rent-seeking activities rather than lead directly to productive ones. This pattern may be true for many professional workers, such as lawyers, accountants, advertising personnel, and brokers. A fourth possible explanation is the increasing absorption of university graduates by "cost disease" sectors characterized by low productivity growth, such as health, teaching, law, and business (see Baumol, Blackman, and Wolff 1989). These are essentially labor activities and, as such, are not subject to the types of automation and mechanization that occur in manufacturing and other goods-producing industries. Moreover, these industries may be subject to output measurement problems, particularly in regard to quality change.

Second, there is no evidence that computer investment is positively linked to TFP growth. In other words, there is no residual correlation between computer investment and TFP growth over and above the inclusion of OCA as normal capital equipment in the TFP calculation. This result holds not only for the 1960–90 period but also for the 1970–90, 1980–90, 1977–97, and 1987–97 periods. The result also holds among exclusively goods-producing industries and among exclusively manufacturing industries. This finding is not inconsistent with recent work on the subject. Oliner and Sichel

14. It is not possible to use changes in skill levels or education as independent variables since, by definition, they would be associated with shifts in occupational composition.

(2000), for example, found a strong effect of computers on productivity growth only beginning in the mid-1990s, which is beyond my period of analysis.

Third, in contrast, computerization is strongly and positively associated with other dimensions of structural change. These include occupational restructuring and changes in the composition of intermediate inputs. The evidence is a bit weaker for its effects on changes in the composition of industry capital stock.

The bottom line is that the diffusion of IT appears to have shaken up the U.S. economy, beginning in the 1970s. However, it is a technological revolution that shows up more strongly in measures of structural change rather than in terms of productivity, if the previous literature is a good guide on the latter issue. In particular, the strongest results of the effects of OCA on productivity growth are found for the late 1990s in the United States. My results seem to indicate that OCA has had strong effects on changes in occupational composition and input structure dating from the early 1970s.

These two sets of results might reflect the high adjustment costs associated with the introduction of new technology. The paradigmatic shift from electromechanical automation to information technologies might require major changes in the organizational structure of companies before the new technology can be realized in the form of measured productivity gains (see David 1991 for greater elaboration of this argument). The results of computerization are also consistent with an alternative interpretation of its role in modern industry. The argument is that a substantial amount of new technology (particularly, information technology) may be used for product differentiation rather than productivity enhancement. Computers allow for greater diversification of products, which in turn also allows for greater price discrimination (for example, airline pricing systems) and the ability to extract a large portion of consumer surplus. Greater product diversity might increase a firm's profits, though not necessarily its productivity. Some evidence on the production differentiation effects of computers is provided by Chakraborty and Kazarosian (1999) for the U.S. trucking industry (for example, speed of delivery versus average load).

APPENDIX

Data Sources and Methods

Capital stock figures. Figures are based on chain-type quantity indexes for net stock of fixed capital in 1992$, year-end estimates. OCA investment data are available for the private (nongovernment) sector only. Source: U.S. Bureau of Economic Analysis, CD-ROM NCN-0229, "Fixed Reproducible Tangible Wealth of the United States, 1925–97."

Educational attainment: (a) Median years of schooling, adult population; (b) percent of adults with four years of high school or more; and (c) percent of adults with four years of college or more. Source: U.S. Bureau of the Census, *Current Population Reports Reports* <www.census.gov/hhes/income/histinc/incperdet.html>. "Adults" refers to persons twenty-five years of age and over in the noninstitutional population (excluding members of the armed forces living in barracks). (d) Mean (or median) schooling of workers by industry for 1950, 1960, 1970, 1980, and 1990 is derived from the decennial U.S. Census of Population Public Use Samples for the corresponding years.

Input-output data: The original input-output data are eighty-five-sector U.S. input-output tables for 1947, 1958, 1963, 1967, 1972, 1977, 1982, 1987, 1992, and 1996 (see, for example, Lawson 1997 for details on the sectoring). The 1947, 1958, and 1963 tables are available only in single-table format. The 1967, 1972, 1977, 1982, 1987, 1992, and 1996 data are available in separate make and use tables. These tables have been aggregated to forty-five sectors for conformity with the other data sources. The 1950, 1960, 1970, 1980, and 1990 input-output tables are interpolated from the benchmark U.S. input-output tables.

NIPA employee compensation: Figures are from the National Income and Product Accounts (NIPA) <www.bea.gov/bea/dn/nipaweb/>. Employee compensation includes wages and salaries and employee benefits.

NIPA employment data: Full-time-equivalent employees (FTE) equals the number of employees on full-time schedules plus the number of employees on part-time schedules converted to a full-time basis. FTE is computed as the product of the total number of employees and the ratio of average weekly hours per employee for all employees to average weekly hours per employee on full-time schedules. Persons engaged in production (PEP) equals the number of full-time-equivalent employees plus the number of self-employed persons. Unpaid family workers are not included.

Research and development expenditures: R&D expenditures performed by industry include company, federal, and other sources of funds. Company-financed R&D performed outside the company is excluded. Industry series on R&D and full-time equivalent scientists and engineers engaged in R&D per full-time equivalent employee run from 1957 to 1997. Source: National Science Foundation <www.nsf.gov/sbe/srs/nsf02312/>. For technical details, see National Science Foundation, *Research and Development in Industry* (Arlington, Va.: National Science Foundation) NSF96-304, 1996.

TABLE

45-Sector Industry Classification Scheme

Industry	1987 SIC codes
1. Agriculture, forestry, and fishing	01–09
2. Metal mining	10
3. Coal mining	11–12
4. Oil and gas extraction	13
5. Mining of nonmetallic minerals, except fuels	14
6. Construction	15–17
7. Food and kindred products	20
8. Tobacco products	21
9. Textile mill products	22
10. Apparel and other textile products	23
11. Lumber and wood products	24
12. Furniture and fixtures	25
13. Paper and allied products	26
14. Printing and publishing	27
15. Chemicals and allied products	28
16. Petroleum and coal products	29
17. Rubber and miscellaneous plastic products	30
18. Leather and leather products	31
19. Stone, clay, and glass products	32
20. Primary metal products	33
21. Fabricated metal products, including ordnance	34
22. Industrial machinery and equipment, exc. electrical	35
23. Electric and electronic equipment	36
24. Motor vehicles and equipment	371
25. Other transportation equipment	37 [exc. 371]
26. Instruments and related products	38
27. Miscellaneous manufactures	39
28. Transportation	40–42, 44–47
29. Telephone and telegraph	481, 482, 484, 489
30. Radio and TV broadcasting	483
31. Electric, gas, and sanitary services	49
32. Wholesale trade	50–51
33. Retail trade	52–59
34. Banking; credit and investment companies	60–62, 67
35. Insurance	63–64
36. Real estate	65–66
37. Hotels, motels, and lodging places	70
38. Personal services	72
39. Business and repair services except auto	73, 76
40. Auto services and repair	75
41. Amusement and recreation services	78–79
42. Health services, including hospitals	80
43. Educational services	82
44. Legal and other professional services and nonprofit organizations	81, 83, 84, 86, 87, 89
45. Public administration	—

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Global Banks, Local Crises: Bad News from Argentina

MARCO DEL NEGRO AND STEPHEN J. KAY

Del Negro is an economist on the macropolicy team, and Kay is a senior economic analyst in the Latin America Research Group in the Atlanta Fed's research department. *They thank Mike Malone, Ann Misback, and John Atkinson for help with the legal issues and Virgina DeJesus-Rueff for help with the data. They are also grateful to Dave Gordon, Jose-Antonio Meade, Carlos Provencio, Myriam Quispe-Agnoli, Will Roberds, Ellis Tallman, and especially Larry Wall for very helpful comments and conversations. Finally, they thank Elena Casal for research assistance.*

Imagine a world where your favorite bank is like Starbucks: you can find a branch at every corner, in every city on the globe. Imagine a world where in emerging markets all banks are international because local banks have either disappeared or been bought out. The world just described is not as distant from reality as one might think, especially in the Americas. Nearly everywhere you go in Latin America, from San Luis Potosí in Mexico to Santiago in Chile, Citibank has an office (see Chart 1). In the last few years, large U.S. and European banks have expanded their presence in several Latin American countries at a staggering pace to the extent that today in some countries they own or control the majority of the domestic banking system.

In the past few decades, banking crises have been a recurrent phenomenon in Latin America.[1] Some have argued that the internationalization of the banking sector has ushered in a new era. A November 2001 report by Salomon Smith Barney states that "One of the main benefits that the presence of foreign banks in Latin America should produce is the overall decline in systemic risk. . . . We believe systemic risk in the [Argentine] banking system (one that caused the collapse of the system of payments) is low, as 43% of its equity is controlled by foreigners"(23). The rationale for this optimism is as follows. When an intermediation sector is purely domestic, any financial crisis, major currency depreciation, or government bankruptcy is a systemic shock that could cause the collapse of the entire system. The fact that international banks now own or control a sizable fraction of local banking systems, the reasoning goes, has changed the picture considerably. Some international banks hold such a large and internationally diversified portfolio of assets that a country-specific shock in a small economy, like Argentina, should not be able to endanger their financial health. Hence, what used to be systemic risk from the perspective of local banks with undiversified portfolios might no longer be systemic from the standpoint of large international banks. In economic terms, Argentina is about the size of Connecticut. Given the size and resources of a typical large international bank, a crisis in a country like Argentina could be overcome by such a bank—or so the reasoning went.

This scenario, if true, would be very good news for depositors in emerging markets. While in the United States deposit insurance shields depositors from the risk of bank insolvency, in some emerging markets there is no deposit insurance at all.[2] In others, like Argentina, its scope and resources are limited.[3] This lack or limitation of deposit insurance in emerging markets means that a shock to the asset side of a bank often translates into a shock to the liability side: Depositors bear at least some of the brunt of bank insolvency, especially when it is systemic. In this light, the international diversification

CHART 1

Citibank Branches in the Western Hemisphere

Source: Citibank <www.citibank.com> (March 2002)

of foreign banks' assets is an attractive feature for depositors in emerging markets because it reduces the portfolio exposure to country-specific shocks and hence makes deposit safer.

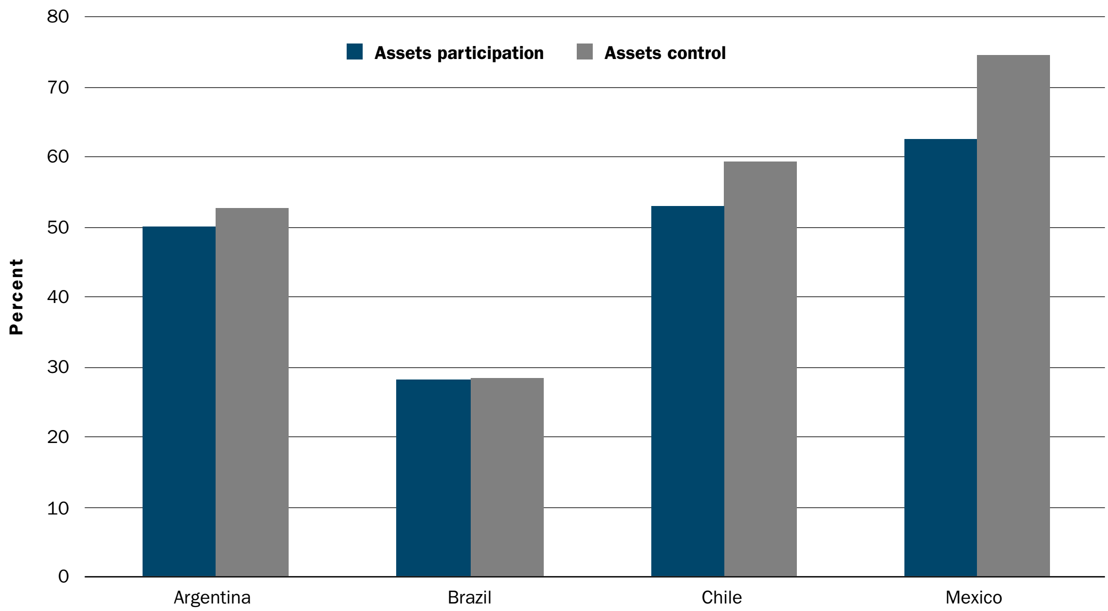
Yet Argentina's experience shows that the presence of international banks was not enough to prevent local banking crises and sizable losses to depositors. Specifically, the point of this article is as follows: The "bad news" from Argentina is that depositors in emerging markets may not reap the full benefits of international portfolio diversification. The article argues that depositors may not reap the full benefits because international banks have limited liability, at least under some circumstances—for instance, whenever the local government heavily intervenes in the banking system. Hence, there is a key difference between a crisis in, say, Connecticut and a crisis in Argentina. If the branch of any bank in Connecticut is producing heavy losses, for example, the U.S. regulator will not simply liquidate the branch and let the parent company—that is, the bank—forfeit its obligations to the depositors at that branch. The parent company has no choice but to face its liabilities, at least to the extent that the bank as a whole is solvent. If the same events occur at the bank's branch in Argentina, however, the bank can conceivably refuse to shore up the local branch—or at least threaten to do so—even if the parent company as a whole has enough liquidity to withstand the crisis.[4] Because of this limited-liability feature, the Argentine branches or subsidiaries of international banks may face the crisis as stand-alone entities. And while the parent company's portfolio is highly diversified internationally, the branch's or subsidiary's portfolio often is not.[5]

Given the sensitive nature of this topic, it is important that the message of this article is not misunderstood. The article does not argue that the presence of international banks is detrimental to emerging markets. On the contrary, there is substantial evidence that opening the banking system to foreign banks is beneficial to emerging markets from all points of view, including macroeconomic stability. Also, the article does not argue that the limited-liability feature itself is detrimental for emerging markets. While the limited-liability feature of international banks may seem bad ex post—and, of course, it is from the perspective of Argentine depositors—this feature may well be desirable, perhaps even necessary, ex ante. Indeed, the earlier analogy comparing a crisis in Connecticut and one in Argentina needs at least one important qualification. In the unlikely event that the State of Connecticut were to implement some of the actions taken by the Argentine government—such as forced conversion of dollar-denominated bank assets into pesos at a less-than-market rate or limitations on holdings of dollar-denominated assets—the banks could certainly challenge those actions in a federal court.[6] International banks do not have this option in the Argentine case. Hence, the limited-liability feature is needed to protect banks from foreign governments' actions; in the absence of limited liability, the incentive for foreign government to (implicitly or explicitly) expropriate the assets of international banks would be too high. Although this article does not study the welfare implications of this limited-liability feature, the concluding section offers some further thoughts on the issue. In particular, it argues that the limited-liability feature may also create perverse incentives for international banks to the extent that local depositors are not fully aware of it.

This article first presents some evidence of the globalization of the banking sector in Latin America,

CHART 2

Foreign Banks' Participation and Control as a Percentage of Total Sector Assets, November 2001



Source: Salomon Smith Barney (2001)

documenting the dramatic increase of the phenomenon in the late nineties. The discussion also demonstrates that the involvement of international banks in any country has often been very large relative to the size of the banking sector in that specific country but relatively small in comparison to the overall size of the international bank. The article then reviews the literature on the pros and cons of international banks in emerging markets, specifically in Latin America. The discussion focuses on the literature that addresses the question, Does the presence of foreign financial institutions enhance or reduce the stability of the domestic banking system? The study then examines the legal issues that are behind the limited-liability feature. Indeed, the institutional information in this section, which is sometimes neglected by the literature, is the main value added of this article. Finally, the article addresses the "bad news" from Argentina and discusses some implications of this phenomenon.

International Banks in Latin America: Some Facts

In the largest Latin American countries a sizable portion of the banking sector is, directly or indirectly, in the hands of international financial institutions. Chart 2 shows the percentage of assets controlled by foreign banks in the four largest Latin American banking systems. The definition of "control" is the same used in the report by Salomon

1. Since 1980, Argentina alone has suffered two banking crises, in 1980–82 and 1989–90 (see Caprio and Klingebiel 1996).
2. In the United States the Federal Deposit Insurance Corporation (FDIC) covers deposits up to $100,000. Before the FDIC Improvement Act (FDICIA) of 1991, essentially all creditors of large banks were covered by the FDIC. FDICIA substantially limits this coverage (see Wall 1993).
3. Kane and Demirgüc-Kunt (2001) document that deposit insurance has become very popular of late in emerging markets: In the past fifteen years the fraction of countries offering deposit insurance has increased from about 30 percent to 70 percent. The remainder of the paper provides further details on the deposit insurance scheme in Argentina.
4. Of course, international banks can close their operations in emerging markets at will, but the point addressed in the article is the circumstances under which international banks have limited liability.
5. Some argue that this lack of diversification was partly due to the Argentine government's forcing banks to hold government paper.
6. In 1933 the federal government actually implemented both actions: It suspended the gold clauses (which tied the value of certain assets to gold) and forced all private parties to hand all gold (coins, bullions, and certificates) to the federal government. Those actions were challenged in federal courts and finally in the Supreme Court. In all (four) cases, the Supreme Court sided with the federal government (Kroszner 1999).

TABLE 1

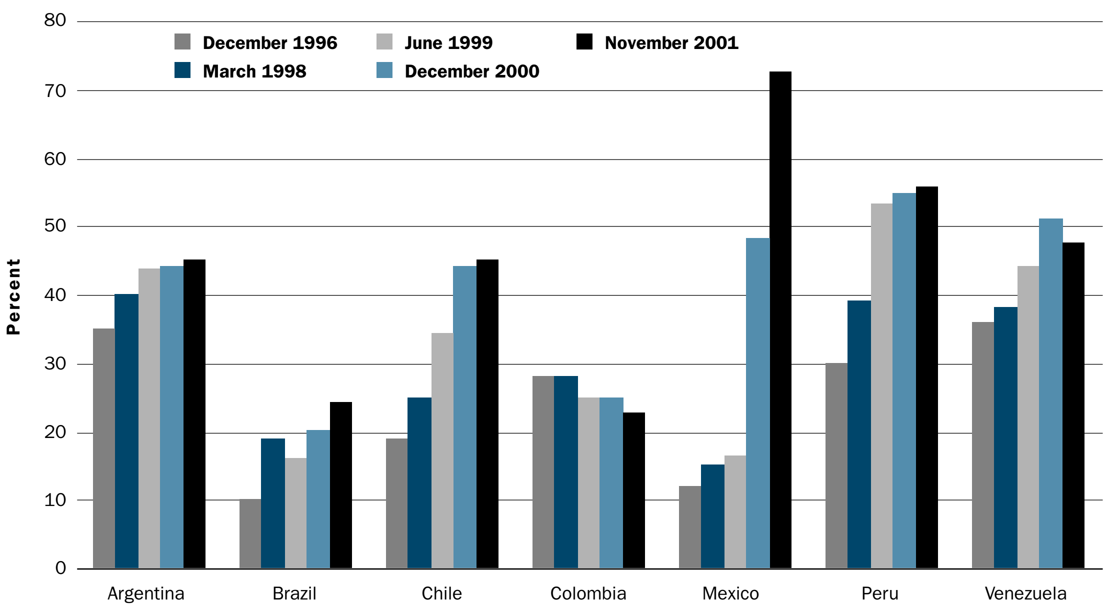
Foreign Participation and Control of Loans, Deposits, and Equity, November 2001

	Loans control	Loans participation	Deposits control	Deposits participation	Equity control	Equity participation
Argentina	46.5	44.2	46.4	43.3	43.1	40.5
Brazil	24.4	24.6	16.3	16.5	30.1	29.8
Chile	44.9	36.0	44.5	36.4	54.1	46.4
Mexico	72.9	57.7	76.2	60.7	74.8	61.1

Note: All figures are percentages. November participation is applied to June 2001 figures.
Source: Salomon Smith Barney (2001)

CHART 3

Foreign Control of Total Loans



Source: Salomon Smith Barney

Smith Barney from which the data were taken: An international bank controls a domestic bank if its stake in the domestic bank is at least 40 percent.[7] The chart shows that foreign banks control almost a third of banking sector assets in Brazil, the largest Latin American economy. In the second-largest economy, Mexico, the figure rises to a staggering three-quarters. In the third- and fourth-largest economies (in financial terms), Argentina and Chile, foreign banks control 53 percent and 59 percent of total assets, respectively. The numbers for the share of assets owned by international banks ("participation") are lower, but not very much so, suggesting that international financial institutions usually own large stakes in the banks they control.

Table 1 looks at other measures of international banks' involvement in Latin America, particularly the share of loans, deposits, and equity either controlled or owned by foreign financial institutions in the four largest Latin American countries. In Brazil international banks control a quarter of loans, 16 percent of deposits, and 30 percent of equity. The corresponding figures for Mexico are 73 percent, 76 percent, and 75 percent. For Argentina and Chile these figures are approximately 40 percent to 50 percent. The table clearly shows that, no matter how one measures it, the presence of international banks in Latin America is large.[8]

The picture just described would have been almost unthinkable a decade ago. Chart 3 shows the dramatic expansion of foreign control of total loans in the banking sector from December 1996 to November 2001. Foreign control over loans increased by 30 percent in Argentina, more than doubled in both Brazil and Chile, and increased sixfold in Mexico. Table 2, which lists foreign control of total assets in the banking sector in 1994, 1999, and 2001, also shows how rapidly foreign control evolved in the 1990s. Foreign control of assets in Mexico evolved from 1 percent in 1994 to 45 percent in 2001.[9] In Argentina, Brazil, and Chile, foreign control of total assets tripled during that period.

Explaining this dramatic increase in foreign banks' presence in Latin America goes beyond the scope of this article. According to the literature (Clarke and others 2000; Clarke and others 2001; Barajas, Steiner, and Salazar 2000; Demirgüc-Kunt and Huizinga 2000), one reason for this increase seems to be that domestic banks were not very efficient, at least relative to foreign banks. Since competition from local banks in emerging markets is often not as stiff as competition at home, for many U.S. and European banks the Latin American market opens profit opportunities in the provision of financial services. In some countries, the increase in economic integration between the home country and the host country also prompted those international banks that wanted to "follow their clients" to expand their role in Latin America. For instance, since the beginning of the North American Free Trade Agreement (NAFTA) in 1994, economic integration between the United States and Mexico has increased dramatically. Changes in regulations have also played a major role. In Mexico, before NAFTA, Citibank was the only international bank permitted to conduct (limited) banking operations. Until December 1998 regulations prohibited foreign control of Mexico's three largest banks, which account for about 60 percent of loan market share. The lifting of those restrictions prompted a dramatic expansion of foreign banks' role in Mexico.

TABLE 2

Foreign Control of Total Assets, 1994–2001

	1994	1999	2001
Argentina	17.9	48.6	53.1
Brazil	8.4	16.8	27.0
Chile	16.3	53.6	48.0
Mexico	1.0	18.8	45.4

Note: Control is defined as a 50 percent stake.
Source: IMF, Salomon Smith Barney, authors' calculations

Finally, financial crises themselves contributed to the increasing presence of international financial institutions in Latin America (see Peek and Rosengren 2000b). In the aftermath of the Mexican crisis, for instance, the government was very eager to sell the banks it had just rescued. International banks were an important source of new capital for a banking sector that desperately needed a capital infusion. The same situation occurred in Argentina in the aftermath of the Tequila Crisis.

Which international banks are the biggest players in the Latin American arena? For each of the largest eight financial institutions involved in Latin America, Table 3 shows the amount of loans made by banks controlled by these institutions and these loans as a percentage of total loans. Three of the banks shown in the table are a notch above all others in terms of involvement in Latin America: two Spanish banks, BBVA and Santander Central Hispano (SCH), and a U.S. financial institution, Citigroup.

How large a stake do international banks have in Latin America? Table 4 lists the amount of loans that the three major players control in the four largest banking sectors in the region.[10] The table indicates that loans made to these four countries represent a sizable portion of the loan portfolio of these banks. For Citigroup this share is roughly 9 percent. For the two Spanish banks the figure is even

7. If a 50 percent threshold is used the figures do not change substantially, with the exception of Mexico, where the Spanish bank Banco Bilbao Vizcaya Argentaria (BBVA) owns 49 percent of BBVA Bancomer.
8. Peek and Rosengren (2000b) argue that all these measures grossly underestimate the importance of international banks for lending to Latin America. The asset and loan measures include subsidiaries and branches of international banks that operate in the host countries but neglect offshore lending. Peek and Rosengren show that until 1997 the latter component was more important than the former for Argentina, Brazil, and Mexico.
9. In this case, control is defined as at least a 50 percent stake. This definition excludes Mexico's largest bank, BBVA Bancomer, of which the Spanish bank BBVA owns a 49 percent stake. If the lower 40 percent threshold is used, foreign control of total assets would be 73 percent.
10. Again, these figures actually underestimate the exposure of international banks because they do not include offshore lending (Peek and Rosengren 2000b). One should also be careful in interpreting these figures as appropriate measures of risk, which is more properly computed from the exposure in relation to the parent bank's capital or equity rather than the overall asset position (see Goldberg 2001).

TABLE 3

Top Eight Foreign Banks in Argentina, Brazil, Chile, and Mexico, 2001[a]

Bank	In U.S.$ billions	As a percent of total loans
Banco Bilbao Vizcaya Argentaria (Spain)	36.6	11.5
Santander Central Hispano (Spain)	34.5	10.8
Citibank (U.S.)	34.8	10.9
FleetBoston (U.S.)	9.2	2.9
HSBC (U.K.)	5.1	1.6
ABN Amro (Netherlands)	4.5	1.4
Scotiabank (Canada)	4.1	1.3
Sudameris (France/Italy)	3.7	1.2

[a] As a percentage of total loans controlled
Source: Salomon Smith Barney

TABLE 4

The Largest Three Foreign Banks' Loans to Argentina, Brazil, Mexico, and Chile

Bank	Net loans	Loans to top four banking sectors	As % of net loans	Loans to Argentina	As % of net loans	Loans to Brazil	As % of net loans	Loans to Mexico	As % of net loans	Loans to Chile	As % of net loans
SCH	154.9	34.3	22.1	6.5	4.2	2.4	1.6	14	9.1	11.4	7.4
Citigroup	381.8	34.6	9.1	4.7	1.2	3.3	0.9	25	6.6	1.6	0.4
BBVA	133.9	36.7	27.4	5.0	3.7	1.2	0.9	28	20.9	2.5	1.9

Note: In billions of U.S. dollars and as a percentage of total loans. Loans are shown in billions of U.S. dollars. Net loans are total loans less loan loss reserves as of year-end 2001. Country loans are as of November 2001.
Source: Dow Jones Interactive, Salomon Smith Barney

larger, about 22 percent for SCH and 29 percent for BBVA. On the one hand, these numbers suggest that these banks, especially SCH and BBVA, could be severely affected by a systemic crisis in Latin America as a whole. On the other hand, if one focuses on any specific country, one finds that, with the exception of Mexico, the exposure of these banks is relatively small. For Argentina the share of net loans is around 4 percent for the two Spanish banks and a mere 1.2 percent for Citigroup. In Mexico, by contrast, international banks have quite a bit at stake: 6.6 percent of Citigroup's net loans, 9.1 percent of SCH's net loans, and 20.9 percent of BBVA's net loans.

Foreign Banks and Domestic Crises: What Do We Know?

The literature on international banks in Latin America (and elsewhere) is relatively recent, just like the phenomenon it studies. The literature can best be understood within the context of the policy questions faced by decision makers in Latin America and other developing countries: Should we allow entry to foreign banks? What are the gains? What are the potential risks? Box 1 offers a brief review of the literature. This review focuses on the evidence the literature has gathered on the narrower questions, Does the presence of foreign financial institutions enhance or reduce the stability of the domestic banking system? What are foreign banks going to do in time of crisis? Given the apparently endemic instability of Latin American economies, these are key questions policymakers face. Opponents of foreign bank entry claim that in a crisis international banks will abandon—"Vive les rats!"—the domestic economy to its destiny. Proponents argue that, on the contrary, global banks will provide stability to the domestic financial sector since they are less affected by shocks that are idiosyncratic to the host country.

In principle, the presence of foreign banks has two contrasting effects on the stability of domestic bank-

BOX 1

International Banks in Latin America: The Literature

The literature on international banks in Latin America can be best understood within the context of the policy questions faced by decision makers in Latin America and other developing countries: Should we allow entry to foreign banks? What are the gains? What are the potential risks?[1]

One of the main benefits related to the entry of foreign banks is the increased efficiency of the financial system. On this point, the literature strongly suggests that efficiency increases following foreign banks' entry into developing countries.[2] For one thing, banks that expand abroad are typically the "best of the crop" in the country of origin (Focarelli and Pozzolo 2000). Hence, they are likely to export improved management and information technology practices to the host country. Second, the literature finds that foreign banks are generally more efficient than domestic competitors (Barajas, Steiner, and Salazar 2000; Clarke and others 2000). Third, a number of studies find that foreign bank entry has been associated with increased efficiency of domestic financial intermediaries (see Claessens, Demirgüc-Kunt, and Huizinga 1998; Clarke and others 2000).

The payoff from increased efficiency can be very large. Levine (2001) argues that there is substantial empirical evidence supporting the following causal chain: first, foreign bank entry enhances the efficiency of the banking sector; second, efficiency in the intermediation sector spurs growth by boosting productivity.

Opponents of financial openness, however, emphasize the other side if the coin. By squeezing the interest margins and profitability of domestic banks, the entry of foreign banks may push local intermediaries out of the market. This reasoning implies that entire sectors that were previously dependent on local banks—small firms, for instance—may find themselves without access to credit, with detrimental consequences for the economy. The evidence on whether these consequences actually ensue in countries with extensive foreign bank presence is inconclusive. The literature finds that small businesses are indeed less likely than larger ones to receive credit from foreign banks (Berger, Klapper, and Udell 2000; Clarke and others 2002). After the size of the banks in the sample is controlled for, however, the negative relationship between foreign ownership and lending to small businesses tends to disappear, if not to be reversed. A different but related argument brought forward by opponents of foreign banks' entry is that these banks tend to "cherry-pick" their customers, leaving domestic banks with a worse pool of potential creditors than before. There is little evidence supporting this point, however, and the existing evidence points in the opposite direction (Crystal, Dages, and Goldberg 2001).

The multitude of banking crises during the last two decades point to the weaknesses of the regulatory and supervisory environment in many emerging markets. Disclosure standards are also inferior in developed countries, especially to standards in the United States. Proponents of financial openness argue that, by allowing foreign bank entry, emerging markets indirectly benefit from the more advanced supervisory and disclosure environment in the country of origin (see Peek and Rosengren 2000b). Opponents of financial openness counter that foreign bank entry leaves the domestic regulator in a weaker position than before. For one thing, the regulator's ability to exercise moral suasion is lessened. In addition, foreign banks may be more responsive to changes in regulations at home than in the host country (Peek and Rosengren 2000b). Specifically, regulatory changes in the country of origin may affect lending in the host country.

1. An exhaustive review of the literature so far can be found in Clarke and others (2001).
2. This evidence for developing countries is in contrast to that found for developed countries, in particular for the United States (see, for instance, Hasan and Hunter 1996).

ing systems (leaving aside the issue of limited-liability, which will be discussed later). On the one hand, the portfolio diversification of global banks makes the domestic financial system less fragile with respect to domestic shocks. On the other hand, their presence means that the host country may become more exposed to external shocks—more specifically to shocks that affect the country of origin of the banks.

Global banks are generally larger, and have a more diversified portfolio of assets, than local banks.[11] The international portfolio diversification of global banks is advantageous for the host country's financial system both ex post, in the event of a crisis, and ex ante. If a crisis occurs, global banks are likely to have both less portfolio exposure to the domestic economy and greater access to liquidity than local banks do. Ex ante, according to standard portfolio theory, the presence of international banks may imply that the interest rate paid on loans by domestic firms is lower, other things being equal, than when only local banks are present. Since local banks have all their eggs in the same basket, they are willing to add one more egg to that same basket only if the price is high enough to compensate them for the additional risk they are undertaking. Global banks have their eggs in many baskets. Hence, the additional risk undertaken by international banks of putting one more egg in the Argentine basket is lower than that undertaken by an Argentine bank, so the international banks might be willing to demand a lower return. In equilibrium, depending on the market structure of the banking system, this willingness to demand a lower return may translate into a lower cost of capital for domestic firms.

Foreign banks' entry can in principle have two contrasting effects on the domestic financial system—diminished sensitivity to domestic shocks and higher exposure to shocks in the international banks' country of origin.

In a nutshell, whenever the banking system is closed, country-specific shocks are necessarily systemic and hence may threaten the stability of the system. From the perspective of international banks, however, those very same shocks are idiosyncratic. Hence, the entry of international banks makes the domestic financial system less fragile with respect to domestic shocks.[12] An important corollary of this point is the following: The high volatility of Latin American economies is not at all an obstacle to the expansion of international banks, at least to the extent that this volatility is idiosyncratic.[13] On the contrary, the higher the volatility is, the higher the relative advantage of foreign versus domestic banks.

The discussion now turns to the second question: Does the presence of foreign banks mean that the host country may inherit global shocks? Even in the absence of foreign banks, emerging markets are certainly not isolated from global financial shocks, as shown very clearly by the Asian crises. Yet some argue that the presence of foreign banks exacerbates the host country's exposure to global shocks. For some global banks, idiosyncratic shocks in the country of origin—Spain, for instance—may affect the lending behavior of their subsidiaries abroad. In addition, Kyle and Xiong (2001) have shown that "contagion" may be the rational outcome of international financial integration via a wealth effect. While international banks are not the focus of Kyle and Xiong's study, the logic of their argument may apply to international banks as well. In summary, a country that opens its banking system to foreign banks may become less sensitive to its own shocks but at the same time increase its exposure with respect to shocks generated elsewhere.

Empirically, there is some evidence that both effects are at work—that foreign banks' entry makes the banking system (1) less sensitive to domestic shocks and (2) more sensitive to external ones. On the first point, the evidence suggests that lending by global banks is stronger and more stable than lending by domestic financial institutions even in the face of crises in the host country. Dages, Goldberg, and Kinney (2000) show that during the Tequila Crisis foreign banks in both Mexico and Argentina did not "cut and run." The authors find that foreign banks had both the highest loan growth and the lowest volatility in lending growth before, during, and after the crisis for both Argentina and Mexico. Dages, Goldberg, and Kinney also find that lending by foreign banks is less sensitive to changes in domestic real GDP growth than is lending by domestic banks although their research cannot statistically reject the hypothesis that private domestic and foreign banks have the same proportionate response to cyclical forces.[14] Goldberg (2001) also shows that U.S. banks' claims on emerging markets are not highly sensitive to fluctuations in local-country GDP. A study by Demirgüc-Kunt, Levine, and Min (1999), based on the work of Demirgüc-Kunt and Detragiache (1997), finds that the presence of foreign banks reduced the likelihood of a banking crisis in the host country.[15]

A related issue, investigated by Crystal, Dages, and Goldberg (2001), is whether foreign-owned banks are any sounder in terms of lending practices than domestically owned ones. Crystal, Dages, and Goldberg find that in the seven largest Latin American economies, foreign-owned banks fare marginally better than local ones in terms of financial strength ratings (Moody's Bank Financial

Strength Ratings) although there are no significant differences between foreign and private domestic banks. For Argentina, Chile, and Colombia, the authors examine banks' balance sheet data and find that foreign banks tend to have more aggressive loan provisioning and higher loan recovery rates than domestically owned banks do. In summary, the findings of Crystal, Dages, and Goldberg suggest that foreign banks' entry may lead to a sounder banking system in the host country.

The fact that international banks are perceived to be sounder than local banks in times of crises has led some to argue that foreign banks' presence opens the possibility of a "capital flight at home." Before the appearance of foreign banks, investing abroad was the only safe haven for domestic depositors, given the lack of credible deposit insurance. Now, under the assumption that foreign banks are strong enough to withstand a crisis, all depositors need to do is transfer their savings from local to foreign financial institutions. There is indeed some evidence of such a "flight to quality" during the Asian crisis and during the Tequila Crisis in Argentina (IMF 2000; also, see Kane 2000 for a discussion of the policy implications of the "flight to quality").[16]

There is also evidence that the presence of foreign banks may increase the host country's exposure to home country shocks. Specifically, evidence shows that lending by international banks responds to economic fluctuations in the country of origin. Peek and Rosengren (2000a) have widely documented that the lending behavior of Japanese banks in the United States was heavily conditioned by events at home and that these changes in the lending pattern had real effects in the host country. Goldberg (2001) studies the determinants of U.S. banks' claims to emerging markets. She finds that the relationship between claims to Latin America and movements in U.S. real GDP growth is significantly procyclical even after controlling for fluctuations in local GDP and local and U.S. interest rates.

In summary, foreign banks' entry can in principle have two contrasting effects on the domestic financial system—diminished sensitivity to domestic shocks and higher exposure to shocks in the international banks' country of origin. In addition, both effects are empirically relevant, raising the question of which of the two is the most important quantitatively. Although no study to our knowledge directly addresses this question (except perhaps Demirgüc-Kunt, Levine, and Min 1999), the first effect is likely to be more important than the second for Latin American countries. Latin American economies have historically been very volatile, and these fluctuations have had a disrupting impact on the local banking system. Therefore, it is likely that the gains from a diminished sensitivity of lending to local shocks outweigh the costs of higher sensitivity to shocks originated elsewhere. The results from the existing literature suggest that foreign banks' entry is likely to make the banking system more stable. To what extent do the recent events in Argentina lead us to reassess this conclusion, if at all? This question is addressed later in the article, but the next section takes a brief detour into some relevant legal issues.

11. Goldberg (2001) shows that 60 percent of the exposure of large U.S. banks engaged in international lending is in industrialized countries.
12. The next two sections of the article argue, however, that the limited-liability feature of international banks undermines some of the benefits from international portfolio diversification.
13. This point is forcefully made in Stockman (2001). Stockman discusses a related issue, namely the idea of an "optimum central bank area," in opposition to the standard "optimum currency area." The "optimum currency area" literature emphasizes the supposed disadvantages of having asymmetric (that is, uncorrelated) shocks. The idea of an optimum central bank area emphasizes the advantages of uncorrelated shocks from the perspective of a central bank.
14. For Mexico, the above statements hold true for banks with similar impaired loan ratios. For developed countries some of the evidence suggests otherwise. Tallman and Bharucha (2000) find that in Australia during the 1986–93 credit crunch foreign banks cut lending more than domestic ones did.
15. Interestingly, these authors find that the significant variable in reducing the likelihood of a crisis is not so much the share of foreign banks but rather the number of foreign banks.
16. Some authors further argue that "in countries that allow foreign currency deposits, depositors may be more comfortable placing such deposits in foreign banks that have ready access to foreign currency during a banking crisis, with the lender of last resort for the bank being the central bank in the banks' home country rather than that of the host country" (Peek and Rosengren 2000b, 49). In essence, these authors argue that in the absence of limited liability the parent company may have to shore up local branches or subsidiaries. To the extent that this operation affects the solvency of the parent company at home, the home regulator may end up implicitly bailing out the host country banking system. However, because of the limited-liability feature of international banks, it is unlikely that the home country central bank would end up acting as a lender of last resort, particularly if the banking crisis is accompanied by interventions on the part of the foreign government, as was the case in Argentina. The next section directly addresses this issue.

Legal Niceties

What is the relationship between the foreign subsidiary of an international bank and the parent company? If the foreign subsidiary or branch is insolvent, to what extent can depositors or other creditors successfully seek payment from the parent company? If a U.S. bank decides to close down a branch in, say, Connecticut, depositors can withdraw their money at any other branch in the country. Does the same apply to depositors of a U.S. bank's branch in a Latin American country, say, Argentina? If not, why not? We are not experts in international law and hence do not pretend to give a definite answer to these questions. Rather, the goal of this section is to raise these questions—arguing that they are relevant for the issues discussed here—and provide some guidelines for addressing them.

> **"A member bank shall not be required to repay any deposit made at a foreign branch . . . if the branch cannot repay . . . due to . . . an action by a foreign government. . . ."**
>
> **Section 326, Riegle-Neal Act**

The questions posed above have a clear practical relevance for Argentine depositors. They are also relevant for the larger issues discussed in this article, namely, To what extent do depositors reap the benefits of the fact that global banks have an internationally diversified portfolio? To the extent that a global bank can walk away from a country in crisis without being held accountable for the subsidiary's or the branch's liabilities, an incentive arises to pull out if these liabilities exceed the expected profit from remaining in the country. Hence, at least under some circumstances, the presence of international banks may be no safety net for local depositors during a crisis. These questions are also relevant for home and host country regulators.[17] To the extent that foreign banks have a limited liability, the home country regulator may not be as concerned about the repercussions of foreign banking crises on the financial health of the parent company as it would be otherwise.

This discussion has argued that the above questions are relevant. To address them, let us first consider the case in which the parent company's subsidiary, or the branch, operates in the United States. In the case of the subsidiary the key notion is the one of "corporate veil" (see Cox, Hazen, and O'Neal 1997 and Hamilton 1991). A subsidiary's creditors cannot go after the parent company's assets in case of default only if the corporate veil is in place. Loosely speaking, the corporate veil is in place when the following two conditions are satisfied. First, the subsidiary must present itself to creditors as a clearly separate entity from the parent company. Second, it must act as such—that is, the subsidiary must be independently managed, and the parent company must have no more clout than the majority shareholder in any other corporation. If the subsidiary is a bank, a regulator in the United States is particularly keen on enforcing the corporate veil.[18] To prevent claims on deposit insurance, the regulator wants to avoid a situation in which the subsidiary endangers its financial health by making transfers (sweetheart loans, etc.) to the parent company. Just like any other shareholder, the parent company can profit from the subsidiary only via the dividends it receives. In the case of a domestic branch there is of course no corporate veil. Hence, a bank is fully liable for all of its branches, at least those within the United States.

When the subsidiary operates abroad, the corporate veil argument suggests that the parent company is in general not liable for obligations undertaken by its subsidiaries. In order to obtain payment from the head office, creditors would have to show that the corporate veil has been pierced. In recent court cases—such as the one filed in Spain against BBVA (Reuters Business Briefing, June 18, 2002)—Argentine depositors are arguing that the corporate veil between local subsidiaries and the parent company was thin. As discussed above, in the United States the corporate veil is in place to the extent that the subsidiary presents itself to creditors as a clearly separate entity from the parent company. Some of the success of global banks in attracting deposits, Argentine depositors argue, derived precisely from the fact that they marketed themselves as being "safer" than local banks because they have the backing of the parent company. In times of crises this backing is the main motivation behind the flight to quality. Bank advertising tended to stress the reliability of the corporate name, which further reassures depositors that their money is secure.[19]

In the case of foreign branches the distinction between a branch and a subsidiary is often more blurred than in the United States. In several countries, such as Argentina, branches of international banks are essentially treated as separate entities from the head office by the domestic regulator. For instance, foreign branches have to meet capital requirements as a separate entity, that is, without relying on the parent company's capital.

Most importantly for branches of U.S. banks, section 25C of the Federal Reserve Act (section 326 of the Riegle-Neal Interstate Banking and Branching Efficiency Act, codified at 12 U.S. Code section 633) establishes that foreign branches have limited liability under some circumstances:

> A member bank shall not be required to repay any deposit made at a foreign branch of the bank if the branch cannot repay the deposit due to (1) an act of war, insurrection, or civil strife; or (2) an action by a foreign government or instrumentality (whether de jure or de facto) in the country in which the branch is located; unless the member bank has expressly agreed in writing to repay the deposit under those circumstances.

This law was added in 1994 after Citibank was sued by depositors at foreign branches in Vietnam and the Philippines and lost the cases. The Philippine case is particularly instructive. In 1983 the Philippine government had confiscated all foreign exchange, making it impossible for the Manila branch of Citibank to repay Wells Fargo's local subsidiary, Wells Fargo Asia Limited, out of local branch assets. The court ruled that "Citibank's worldwide assets were available for satisfaction of Wells Fargo Asia Limited's claims" in spite of the fact that the original contract did not explicitly state so (see *Wells Fargo* 1991). After this and a similar ruling in the Vietnamese case, U.S. lawmakers sought to protect U.S. banks with foreign branches from actions by host-country governments. The 1994 law makes it clear that worldwide assets of a global bank are not in peril if the foreign branch's failure to honor its obligations is the result of a foreign government's intervention. Most analysts regard the Argentine case as falling into this category: The asymmetric conversion of dollar-denominated banks' assets and liabilities (see the next section) and the restrictions on foreign exchange appear to be clear examples of government interventions.

Hence, the chances of Argentine depositors of U.S. banks recovering their funds in the United States are dim. Also, since government intervention of this sort is not at all rare in the event of a banking crisis, the "news" from Argentina may well be relevant for other emerging markets as well.[20]

What would happen in the absence of a foreign government's intervention—that is, if section 326 is not applicable? Consider the following hypothetical scenario: The Argentine government defaults on its debt but refrains from the actions discussed above.[21] Under this scenario, for some Argentine branches or subsidiaries of international banks, locally held assets would still not suffice to cover their deposits. If the parent company refuses to shore up the local branch, can local creditors successfully seek payment from the head office? While this scenario is only hypothetical, one can argue that the question is still relevant to the case of future crises in emerging markets. At least for branches of U.S. banks, deposit contracts generally state that depositors can collect their funds only locally.[22] The contracts also state that the bank-depositor relationship is governed by the local jurisdiction; hence, a U.S. court may refuse to even consider the case (although such a refusal did not

17. This article does not delve into the issue of cross-border supervision. IMF (2000) summarizes the principles and practices of cross-border supervision, with particular reference to the Basel Concordat.
18. According to U.S. law, if a bank holding company owns more than one bank subsidiary, each subsidiary is responsible for losses of other bank subsidiaries owned by the same holding company regardless of whether the corporate veil is in place or not.
19. In the opinion of some analysts, in Argentina "the foreign owners created the illusion that Argentines were depositing their money into a global financial network. Argentines were told that their money was just as safe as if it was deposited in New York, Madrid, or Hong Kong" (Molano 2002).
20. Many previous banking crises in Latin America—for instance, the 1989–90 crisis in Argentina—were also characterized by similar government interventions. One does not need to look far to find evidence of government interventions following large shocks to the economy. Roosevelt's actions in the aftermath of the Great Depression—the abandoning of the gold standard, the Bank Holidays, and the repudiation of the gold clauses—have close parallels with the Argentine government's actions during the current crisis (although the Argentine government imposed a different conversion rate for banks' assets and liabilities). Kroszner (1999) argues that the repudiation of the gold clauses—which is the equivalent of the Argentine's government conversions of all dollar loans into pesos—was actually perceived as a beneficial action by financial markets. Needless to say, the Argentine government was not as successful.
21. The government debt's default could also be considered a form of government intervention. Whether this is the case from a legal perspective, from an economic point of view it is a very different action from, say, a forced conversion of assets: debt holders are fully aware of the possibility that the debt issuer might default and ask for a risk premium as a compensation for the possibility.
22. Of course, this stipulation applies to the extent that the local branch has enough funds to meet its liabilities. To our knowledge, the contracts do not explicitly state what would happen in case of liquidation of the branch.

occur in the court cases mentioned above).[23] A local court may well demand that the parent company honor its obligations, but the court may have little power of enforcement. In conclusion, it is not clear that creditors of branches or subsidiaries can successfully attach the parent company's assets even in the absence of outright government intervention.

Bad News from Argentina

Before the current crisis, the Argentine banking system was hailed as a success story for Latin America (see Kiguel 2002): A 1998 World Bank study rated Argentina's regulatory regime among the top three in emerging markets (see Calomiris and Powell 2000). Because Argentina was under a currency board (so-called convertibility) regime, the central bank was, by law, severely restricted in its role as a lender of last resort.[24] Hence, the regulator had to make sure that the banking system could stand on its own. To achieve this goal, policymakers pursued a two-tier strategy. The first tier consisted of strengthening prudential regulation (see Calomiris and Powell 2000 for an insightful description of Argentine regulatory approach). Capital requirements were stricter than those imposed by the Basel Committee: The capital asset ratio was set at 11.5 percent as opposed to the 8 percent level recommended by the Basel Committee (Kiguel 2002). Furthermore, capital requirements were adjusted depending on the CAMEL rating of the bank.[25]

Before the current crisis, the Argentine banking system was hailed as a success story for Latin America.

To better assess the riskiness of financial institutions, the regulator also required banks to issue subordinated debt for an amount equivalent to 2 percent of deposits (although foreign banks with good credit ratings did not have to comply) and to be monitored by international credit rating agencies. Banks were also subject to liability requirements—that is, reserve requirements for all liabilities (not only for deposits), depending on their maturity. Liability requirements amounted to about 30 percent of the system deposits (Caprio and Honohan 1999). Indicative of the regulator's faith in foreign financial institutions is the fact that as much as 80 percent of the liquidity requirement could be fulfilled by holding balances at qualifying foreign banks, possibly abroad.

Deposit insurance, which had been abolished in 1992, was reinstated in 1995 during the Tequila Crisis—albeit with a limited scope—with the purpose of strengthening depositors' confidence in the banking system. Deposit insurance was funded via a premium on banks that varied from 0.015 to 0.06 percent of deposits and was implemented via an entity (*Seguro de Depositos Sociedad Anonima*, or SEDESA) that by law could not rely on resources from either the central bank or the Treasury. The scheme covered only deposits up to $30,000 and in principle should have been endowed with enough resources to cover 5 percent of deposits. By the end of 2001, however, the fund had only $270 million, which covered about 0.4 percent of all deposits. A key feature of the scheme, particularly in light of what was to follow, was that it could invest up to 50 percent of its assets in government bonds (*Sistema de Seguro* 2002).

The second tier of the strategy consisted in welcoming foreign banks' entry, especially in the aftermath of the Tequila Crisis. Argentina quickly became one of the first countries in Latin America with substantial foreign bank presence. Finally, the central bank set up a contingent credit line with international banks—a partial substitute for the lack of a lender of last resort. The Argentine financial system's ability to withstand the Tequila Crisis without major losses, in spite of large shocks to deposits (Kiguel 2002), and to weather successfully the East Asian, Russian, and Brazilian crises seemed to suggest that Argentina had found the avenue to banking system stability.[26]

Of course, the current crisis changes the picture considerably. The Argentine economy unraveled in 2001, culminating with the collapse of the convertibility plan that had linked the peso to the dollar at parity (see Box 2 for a brief chronology of the Argentine crisis). The default on government debt in December 2001 had devastating consequences for the banking system as a sizable portion of bank assets (about 21 percent in October 2001) was in government liabilities.[27] In November 2001 the government induced the banks to "voluntarily" swap government bonds for illiquid government liabilities, prompting large deposit withdrawals: Deposits fell 24 percent by the end of the year. In the final days of the De la Rua government only a freeze on deposits could prevent a widespread bank run.[28] In January 2002 convertibility ended and the peso underwent a large devaluation. By government decree, in February 2002 all dollar-denominated loans were converted to pesos at one to one while dollar-denominated deposits were converted at 1.4 pesos per dollar. According to Moody's, the banking system's losses as a result of the crisis could reach $54 billion. Deposit insurance quickly ran out of funds (Para Scotia 2002): In February 2002 a presidential decree revised the deposit guarantee law to allow for compensation of depositors via nontradable government securities.[29] Given that a sizable fraction of deposits (72 percent by December 2001) was dollar-denominated, the central bank could hardly intervene as a lender of last resort. By early 2002 international banks were ready to leave the country or at least threatening to do so (Ryst 2002). Given the Argentine government's heavy-handed intervention in the banking system, the analysis of the previous section suggests that at least for U.S. banks the parent company may not be liable for the local branches.

As the crisis unraveled, some of the supposed benefits of international banks did not quite materialize as expected. As mentioned above, one of the main advantages of international banks is that their portfolios are well-diversified and hence can withstand a localized crisis. This advantage was indeed true for many of the international banks involved in the Argentine crisis. However, banks' local branches and subsidiaries, when considered as stand-alone entities, had portfolios that were by and large just as vulnerable as those of domestic banks to the shocks that hit the economy, like the government's default.[30] To the extent that international banks could walk away from the subsidiaries' liability, from the depositors' perspective the local branches or subsidiaries of international banks were indeed stand-alone entities. Interestingly, the data suggest that this fact seemed to be understood by Argentine depositors—although this specific question certainly deserves a much deeper analysis than the one undertaken here. Chart 4 seems to indicate that little or no flight to quality took place as the crisis developed during 2001 except in the very last months. The observed flight to quality was specifically toward branches of foreign banks perhaps because of their lower exposure to government liabilities.[31]

In summary, the bad news from Argentina is that even a sizable presence of global banks may not be enough to protect depositors from the occurrence of a banking crisis. This article argues that one of the reasons why this is the case is that under some circumstances—and most likely under the circumstances that developed in Argentina following heavy government intervention in the banking system—international banks are shielded from their liabilities. In other words, they may not be legally compelled to recapitalize Argentine branches or subsidiaries. As we write, only a few foreign banks (Credit Agricole, Scotiabank) have explicitly abandoned their Argentine branches or subsidiaries. To the extent that Argentine taxpayers will assume at least part of those liabilities or that depositors will be forced into accepting a subpar compensation for their funds, some foreign banks may decide to stay in the end.[32] Negotiations are under way. In these negotiations, a key factor affecting foreign banks' bargaining power has to do with reputation. On the one hand, a default in Argentina may harm the

23. Interestingly, the court's motivation was as follows: "If the goal is to promote certainty in international financial markets, it makes sense to apply New York law uniformly, rather than conditioning the deposit obligations to the vagaries of local law. . . ." (*Wells Fargo* 1991).
24. The 1992 central bank charter barred the central bank from offering either implicit or explicit guarantees for bank liabilities to the extent that these guarantees were backed by fiscal funds (see Schumacher 2000). The central bank was, however, able to extend repos and rediscounts to financial intermediaries, albeit under restrictions, and to change the reserve requirements. During the 1995 Tequila Crisis the central bank used both instruments in order to weather the crisis (see Calomiris and Powell 2000).
25. The CAMEL score is a measure of the financial health of a bank.
26. Schumacher (2000) reports that by December 1995 nine banks had failed, and thirty had been acquired or merged, out of a total of 137 private banks.
27. For subsidiaries of foreign banks the exposure to the government was also around 20 percent. For branches of foreign banks, however, the corresponding figure was much lower—around 10 percent.
28. The freeze on deposits is still in place as this article is written.
29. The deposit law guarantee now states that these securities cannot be endorsed; depositors would have to hold them to maturity. See *Sistema de Seguro* (2002).
30. However, as discussed above, Crystal, Dages, and Goldberg (2001) find that foreign banks' portfolios were in general marginally sounder than those of domestic banks. See also footnote 27.
31. Martinez Peria and Schmukler (2001) study the extent to which depositors discipline banks in Latin American countries.
32. In the 1989 crisis bank deposits were replaced with bonds that traded at a large discount; the swap was known as the Bonex plan. A similar plan, known as Bonex II, is currently been considered by the authorities.

BOX 2

Chronicle of the Argentine Crisis

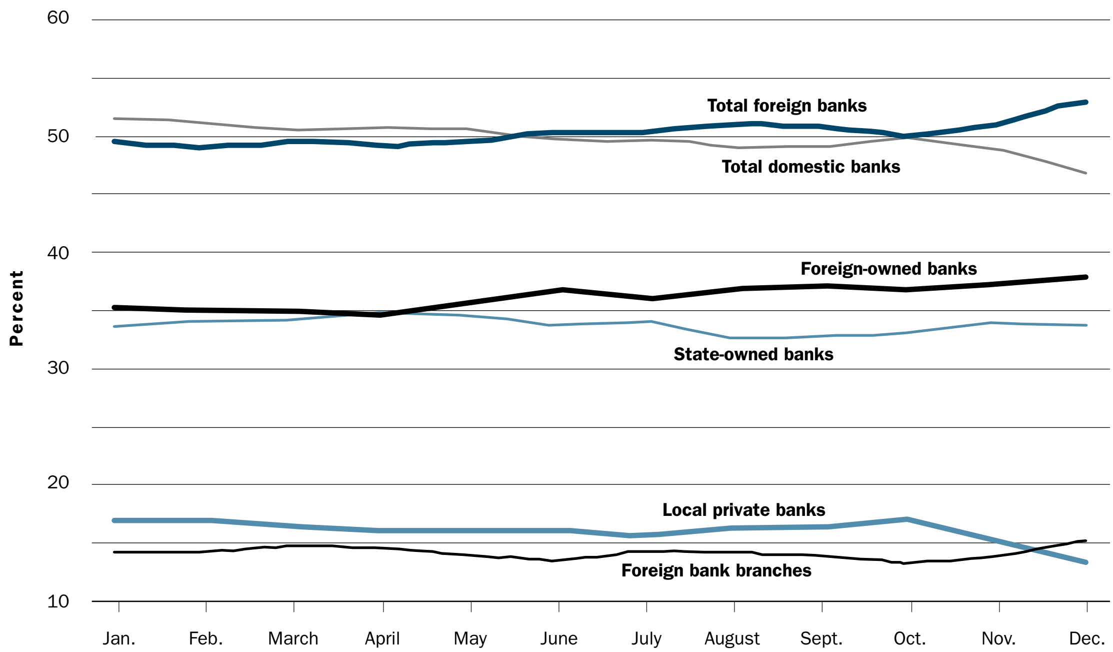
	Events	EMBI+ bond spread over U.S. Treasuries (at end of period)[1]
October 2000	Confidence erodes after Vice President Carlos Alvarez resigns.	815
December 2000	The IMF leads a $39.7 billion three-year rescue package.	773
January 2001	Capital returns to the country, central bank reserves increase $1.3 billion, and deposits increase $1.2 billion.	663
February 2001	Allegations of malfeasance are made against central bank President Pedro Pou. The Turkish crisis begins.	803
March–April 2001	Economy Minister Jose Luis Machinea resigns. His replacement, Ricardo López-Murphy, holds office less than two weeks. Domingo Cavallo takes over. Devaluation fears grow after the Convertibility Law is altered to eventually link the peso with the dollar and the euro.	1,042
June 2001	Argentina completes a $29.5 billion debt swap.	1,025
July 2001	Sharp falls in deposits occur, and bond spreads widen. Congress approves a zero deficit law calling for the immediate cut of the fiscal deficit through budget cuts and tax hikes. Salaries and pensions over $500 are cut by 13 percent.	1,599
August–September 2001	New fiscal austerity measures are enacted. The announcement of an IMF assistance package calms default fears. Unemployment is at 17.2 percent. The IMF announces up to $8 billion of additional loans ($5 billion available immediately and $3 billion available later depending on future reforms).	1,595
October 2001	Opposition Peronists win in legislative elections.	2,136
November 2001	The government announces a new, ostensibly voluntary, debt swap of as much as $16 billion in high-yield government bonds held by local banks and pension funds for securities that pay lower interest but are guaranteed by tax revenue. The IMF endorses the swap. Sovereign bond spreads widen. A sharp decline occurs in deposits. Tax revenue drops, and the zero fiscal deficit plan becomes clearly unsustainable.	3,340

	Events	EMBI+ bond spread over U.S. Treasuries (at end of period)[1]
December 2001	2001 deposits fall from $85 billion to $64.6 billion. 2001 GDP falls 3.9 percent. Restrictions on deposits are imposed in the wake of the run on deposits. Withdrawals are limited to 250 pesos per week (later raised to 1,200 pesos per month). Violent protests occur. Domingo Cavallo and Fernando De la Rua resign. Interim President Rodriguez Saá announces a moratorium on foreign debt.	4,404
January–February 2002	President Eduardo Duhalde is sworn in, and the convertibility law ends. A dual exchange rate is announced in January, and a floating exchange rate is introduced in February. Bank assets are converted to pesos at 1 to 1; liabilities are converted at 1.4 to 1. The banking system is in crisis because of a currency mismatch, a decline in value of asset portfolios, and losses from holdings of $30 billion in government debt. Converting dollar loans at parity could generate losses up to $18 billion for the banking sector. The government announces that bank losses will be partially compensated by issuing bonds and indexing loans to inflation.	4,098
March–April 2002	The largest private bank, Banco Galicia, receives an $800 million bailout from the central bank and fifteen local banks. Foreign banks postpone decisions on recapitalization. The central bank intervenes in a Scotiabank subsidiary. The government continues to negotiate with the IMF. Economy Minister Remes Lenicov resigns after mandatory bonds-for-deposit swaps are rejected. He is replaced by Roberto Lavagna.	4,831
May 2002	Scotiabank (Canada) and Credit Agricole (France) plan to sell or close their Argentine units. Societe Generale (France) agrees to recapitalize its Argentine unit.	6,123
June 2002	Voluntary deposit-for-bond swaps are announced. $9.5 billion in ten-year dollar bonds is to be provided to banks to compensate for losses associated with the devaluation and currency mismatch. Negotiations with the IMF are set to resume.	6,791

1. Bond spreads are from JP Morgan's Emerging Market Bond Index (EMBI+) for Argentina.

CHART 4

Deposit Evolution of Foreign and Domestic Banks in 2001



Source: Banco Central de la República Argentina

position of these international banks in other emerging markets. On the other hand, an unconditional recapitalization of local branches could induce other emerging-market governments to believe that foreign banks may always pick up the bill for their lack of fiscal discipline.

Conclusions

There are interesting similarities between the policy debate that took place in the United States in the 1980s and early 1990s with regard to interstate branching and the current debate in emerging markets on international banks (see IMF 2000). Proponents of interstate branching in the United States saw the gains in efficiency from increased competition and the increased stability due to wider portfolio diversification as the two main benefits from lifting restrictions. Opponents claimed that out-of-state branches would draw funds away from local markets and neglect local small businesses.[33] Likewise, opponents of foreign banks' entry into developing markets claim that these banks neglect lending to small enterprises and may amplify credit rationing in times of crisis. In contrast, proponents of foreign banks emphasize the benefits to be gained from efficiency and portfolio diversification. This article documents that the empirical literature by and large sides with the proponents of global banks' entry. Many of the arguments against international banks do not seem to find empirical support.

This article focuses mainly on the issue of banking systems' stability during a crisis, specifically on the following claim, as summarized in an IMF report: "It has been suggested that foreign banks can provide a more stable source of credit and can make the banking system more robust to shocks. The greater stability is said to reflect the fact that the branches and subsidiaries of large international banks can draw on their parent for additional funding and capital when needed. In turn, the parent may be able to provide such funding because it will typically hold a more internationally diversified portfolio than domestic banks, which means that its income stream will be less correlated with purely domestic shocks" (IMF 2000, 163).[34]

The discussion points out that, at least under some circumstances, international banks may not be fully liable for the obligations of their foreign branches or subsidiaries. Because of this limited-liability feature, local depositors may not reap the full benefits from portfolio diversification offered by the presence of foreign banks. During crises, and especially in cases of crises-cum-government-intervention, the branch or subsidiary may default and depositors may not be able to make claims against the parent company's assets. Hence, under such circumstances, the greater portfolio diversification of international banks is of no avail to local depositors.

These arguments, especially in light of recent events in Argentina, suggest that international banks' presence is not a panacea against banking crises. But it is important to note that this argument should not be taken as an argument against foreign banks' entry. First, it is not clear that a financial system closed to foreign banks would be any better. Past crises in Latin America strongly suggest that it would not. Second, the literature has pointed out a number of other important benefits from foreign banks' entry. Third, it is not clear that a priori the limited-liability feature of foreign banks reduces welfare. One may argue that the limited-liability feature of foreign banks increases the cost of financial crises for governments and thus may induce governments to pursue policies that avoid crises. Finally, in the absence of this feature, the expansion of international banks might not have occurred in the first place. At the same time, however, it is not clear that all the incentives generated by the limited liability feature are in the right direction. To the extent that local depositors are unaware of international banks' limited liability, these banks have an incentive to borrow locally and invest in high-yield government securities: The limited-liability feature, if it applies, covers international banks from the risk of government default. More work at both the theoretical and empirical level is needed to investigate these issues.

33. See Jackson and Eisenbeis (1997) for an empirical refutation of the first point.
34. Note that the IMF report does not necessarily endorse these views.

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