# Information Technology and Productivity: A Review of the Literature

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**Abstract**

In recent years, the relationship between information technology (IT) and productivity has become a source of debate. In the 1980s and early 1990s, empirical research on IT productivity generally did not identify significant productivity improvements. More recently, as new data are identified and more sophisticated methodologies are applied, several researchers have found evidence that IT is associated not only with improvement in productivity, but also in intermediate measures, consumer surplus, and economic growth. Nonetheless, new questions emerge as old puzzles fade. This survey reviews the literature, identifies remaining questions, and concludes with recommendations for applications of traditional methodologies to new data sources, as well as alternative, broader metrics of welfare to assess and enhance the benefits of IT.

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## 1. The "Productivity Paradox"—A Clash of Expectations and Statistics

During the past decade, both academics and the business press have periodically revisited the so-called "productivity paradox" of computers:

While delivered computing power in the United States has increased by more than two orders of magnitude since the early 1970s (Fig. 1), productivity, especially in the service sector, seems to have stagnated (Fig. 2). Despite the enormous promise of information technology (IT) to effect "the biggest technological revolution men have known" (Snow, 1966), disillusionment and frustration with the technology are evident in headlines like "Computer Data Overload Limits Productivity Gains" (Zachary, 1991).

Interest in the "productivity paradox" has engendered a significant amount of research. Although researchers analyzed statistics extensively during the 1980s, they found little evidence that information technology significantly increased productivity. As Robert Solow quipped, "you can see the computer age everywhere but in the productivity statistics."[1]

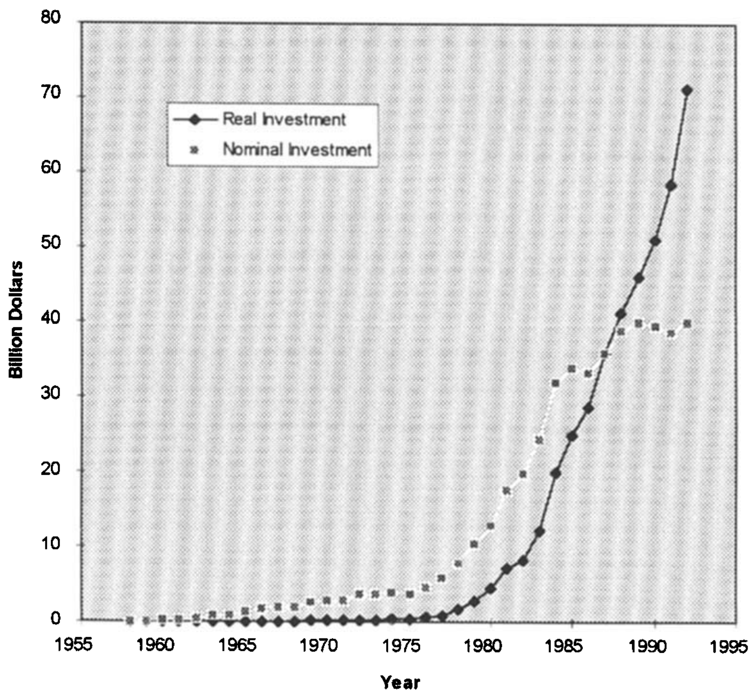



FIG. 1. Investment in information technology is growing at a rapid pace. [Note: Constant dollars (base year 1987) calculated by hedonic price method, see Dulberger (1989).] [Based on data from BEA, National Income and Wealth Division, and adapted from Jorgenson and Stiroh (1995).]

[1] Solow, Robert M., "We'd Better Watch Out," *New York Times Book Review,* July 12, 1987, p. 36.

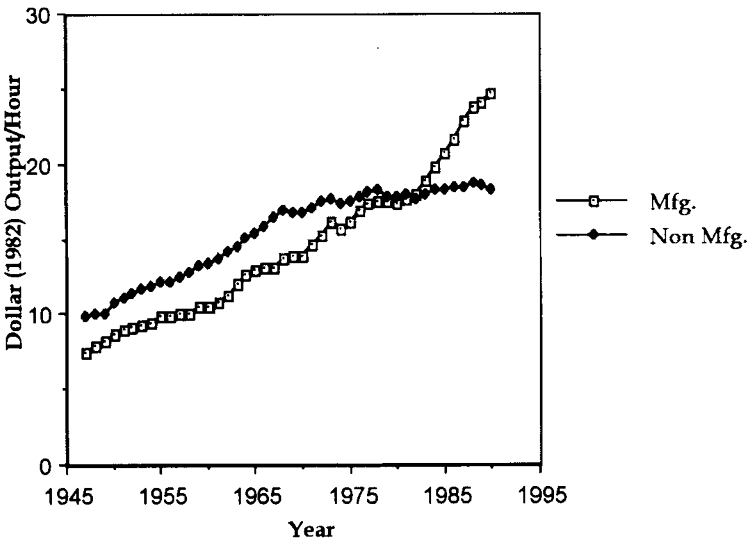



FIG. 2. Productivity in the service sector has not kept pace with that in manufacturing. (Based on data from Bureau of Labor Statistics, Productivity & Testing Division.)

Now, after some researchers found firm-level evidence that IT investments earned hefty returns, the media pendulum has swung in the opposite direction. *Businessweek*'s proclamation of "the productivity surge" due to "information technology,"[2] and *Fortune* magazine's headline heralding the arrival of "technology payoff"[3] represent the latest trend. A growing number of academic studies also report positive effects of information technology on various measures of economic performance.

Just as the business media's premature announcement of a "productivity paradox" was out of proportion to the more carefully worded academic research, the current cover stories on "productivity payoff" are often overblown. A consensus on the relationship between IT investment and economic performance is still elusive. More than a decade ago, one of the earliest surveys concluded that we still had much to learn about measuring the effects of computers on organizations (Attewell and Rule, 1984). A more recent survey also reports a "sobering conclusion: our understanding of how information technology affects productivity either at the level of the firm or for the economy as a whole is extremely limited" (Wilson, 1995).

[2] Wildstrom, Stephen H. "The Technology Payoff," *Businessweek* June 14, 1993, p. 56–68. Mandel, Michael J., "The Digital Juggernaut," *Businessweek,* The Information Revolution, May 18, 1994, Bonus Issue, pp. 22–31. *Businessweek* recently ran another cover story, "Productivity to the Rescue," October 9, 1995.

[3] Magnet, Myron, "Productivity Payoff Arrives," *Fortune,* June 27, 1994, pp. 77–84.

As more research is conducted, we are gradually developing a clearer picture of the relationship between IT and productivity. However, productivity measurement is not an exact science; the tools are blunt, and the conclusions are not definitive. Thus, while one study shows a negative correlation between total factor productivity and high share of high-tech capital formation during the 1968–86 period (Berndt and Morrison, 1995), another study suggests that computer capital contributes to growth more than ordinary capital (Jorgenson and Stiroh, 1995). More recently, Brynjolfsson and Hitt (1996) report positive effects of IT based on firm-level evidence.

This article seeks to summarize what we know; distinguish the central issues from peripheral ones; and clarify the questions that future research should explore. Results and implications of different studies should be interpreted in the context of specific research questions. The question of aggregate economic performance differs from the question of firm-level economic performance. Data sources and performance measures may also depend on the level of aggregation. Even within one level of aggregation, results may depend on the measure of performance or research method. It is hoped that the process of reviewing studies of the productivity mystery will serve as a useful springboard for examining alternative methodologies and the broader issues involved.

As a prelude to the literature survey, it is useful to define some of the terms used and to highlight some of the basic trends in the economics of IT.

### *Definitions:*

- *Information technology* can be defined in various ways. In terms of capital, among the most common is the BEA's (U.S. Bureau of Economic Analysis) category "Office, Computing and Accounting Machinery" (OCAM), which consists primarily of computers. Some researchers look specifically at computer capital, whereas others consider the BEA's broader category, "Information Processing Equipment (IPE)." IPE includes communications equipment, scientific and engineering instruments, photocopiers, and related equipment. In addition, software and related services are sometimes included in the IT capital. Recent studies often examine the productivity of information systems staff, or of workers who use computers.
- *Labor productivity* is calculated as the level of output divided by a given level of labor input. *Multifactor productivity* (sometimes more ambitiously called *total factor productivity*) is calculated as the level of output for a given level of several inputs, typically labor, capital, and materials. In principle, multifactor productivity is a better measure

of a firm or industry's efficiency because it adjusts for shifts among inputs, such as substituting capital equipment for labor. However, the data needed to calculate multifactor productivity are more complex.

- In productivity calculations, *output* is defined as the number of units produced times their unit value, proxied by their *real* price. Determining the real price of a good or service requires the calculation of individual price *deflators* to eliminate the effects of inflation.

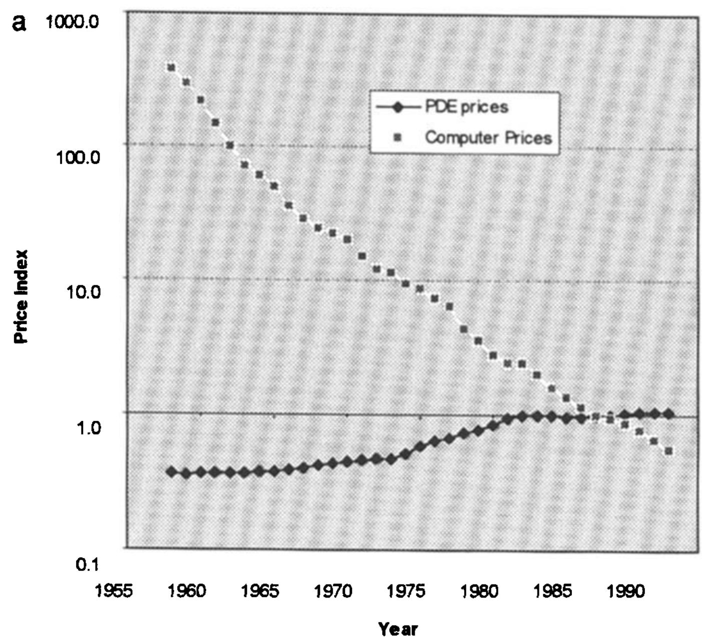
## *Trends:*

- The price of computing has dropped by half every 2–3 years (Figs. 3a and b).[4] If progress in the rest of the economy had matched progress in the computer sector, a Cadillac would cost $4.98, while 10 minutes' labor would buy a year's worth of groceries.[5]
- There have been increasing levels of business investment in information technology equipment. These investments now account for more than 10% of new investment in capital equipment by American firms (Fig. 4, Table II).[6]
- Information processing continues to be the principal task undertaken by America's workforce. More than half the labor force is employed in information-handling activities (Fig. 5)
- Overall productivity growth appears to have slowed significantly since the early 1970s and measured productivity growth has fallen especially sharply in the service sectors, which account for 80% of IT investment (Fig. 2, Table 4).
- White collar productivity statistics have been essentially stagnant for 20 years (Fig. 6).

[4] This relationship has been dubbed "Moore's law" after John Moore, who first documented the trend in microprocessors. It is widely projected to continue at least into the next century. In the last 35 years, the quality-adjusted costs of computing have decreased over 6000-fold relative to equipment prices outside the computer sector (Gordon, 1987b).

[5] This comparison was inspired by the slightly exaggerated claim in Forbes Magazine [1980] that "If the auto industry had done what the computer industry has done, . . . a Rolls-Royce would cost $2.50 and get 2,000,000 miles to the gallon." The $4.98 Cadillac is based on a price of $30,890 for a 1991 Sedan de Ville divided by 6203, the relative deflator for computers. The grocery comparison is based on a wage of $10 an hour and $10,000 worth of groceries, each in 1991 dollars.

[6] Some studies estimate that as much as 50% of recent equipment investment is in information technology (Kriebel, 1989). This higher figure seems to be partly due to a broader definition of IT. A discrepancy also arises when recent investments are expressed in 1982 dollars, when IT was relatively more expensive. This has the effect of boosting IT's *real* share over time faster than its *nominal* share grows. The recent change by BEA to a chain-weighted index, instead of a fixed-weight index, will largely alleviate this problem.



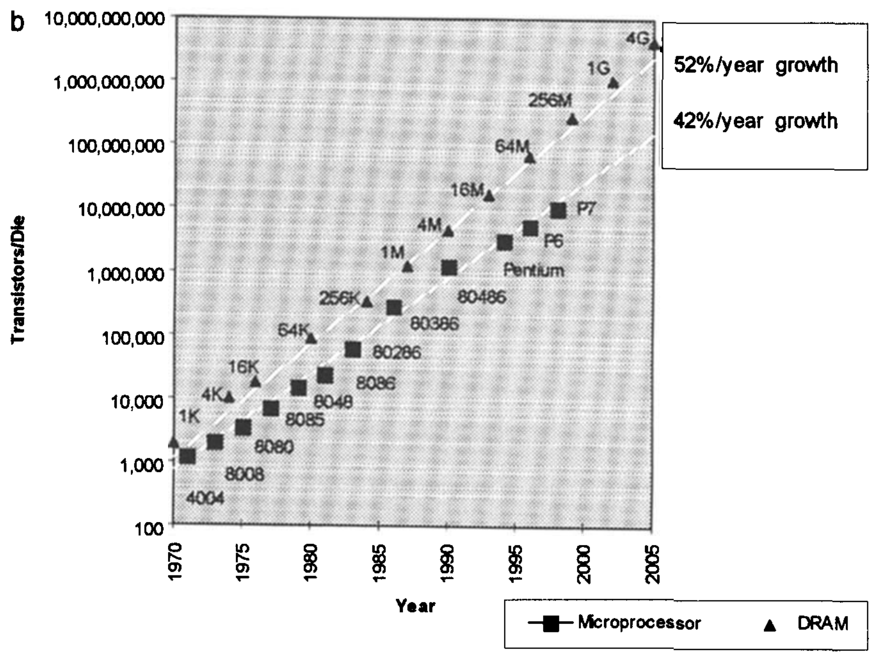




FIG. 3. (a) The cost of computing has declined substantially relative to other capital purchases. PDE, producer's durable equipment. (Based on data from U.S. Department of Commerce, Survey of Current Business.) (b) Microchip performance has shown uninterrupted exponential growth. (P6, P7 microprocessors and 256M, 1G, 4G DRAMs are estimated by Intel and the Semiconductor Industry Association.) [Based on data from Grove (1990), and Intel data. Trend lines are by authors' estimations.]

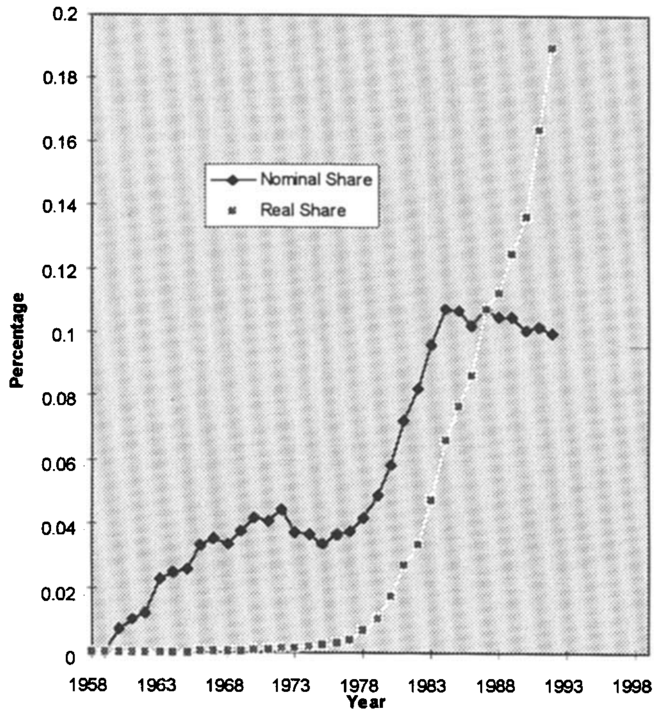



FIG. 4. Computers comprise about 10% of current-dollar investment in PDE. (Based on data from BEA, National Income and Wealth Division.)

These trends suggest the two central questions of the productivity paradox: (1) Why would companies invest so heavily in information technology if it did not add to productivity? (2) If information technology does contribute to productivity, why is its contribution so difficult to measure?

This article builds on a number of earlier literature surveys.[7] This review considers more than 150 articles, but is not comprehensive. Rather, we aim

[7] Much of the material is adapted from a previous paper by Brynjolfsson (1993). Crowston and Treacy (1986) surveyed 11 articles from 1975 to 1985 on the impact of IT on enterprise-level performance and conclude that attempts to measure the impact of IT were surprisingly unsuccessful. They attribute this to poorly defined variables, a result of inadequate reference disciplines and methodologies. A review of research combining information systems and economics, by Bakos and Kemerer (1992), includes particularly relevant work. In addition, many papers that seek to assess IT productivity directly begin with a literature survey; the reviews by Brooke (1992), Barua *et al.* (1991), and Berndt and Morrison (1995) were particularly useful. Most recently, the first part of Landauer (1995) details research on the productivity puzzle. Wilson (1995) also provides a useful survey of articles.

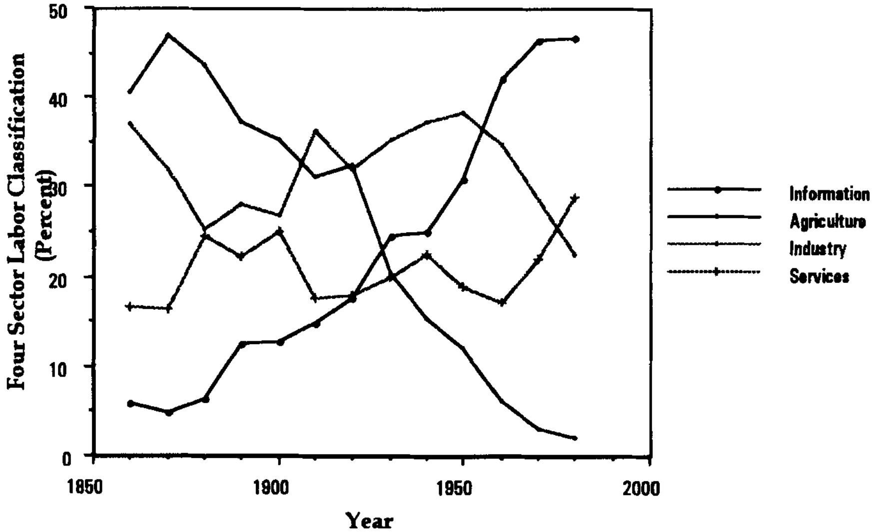



FIG. 5. Information processing is the largest category of employment. The defining criterion for information workers is whether the primary activity is knowledge creation, warehousing, or dissemination. [Based on data from Porat (1977).]

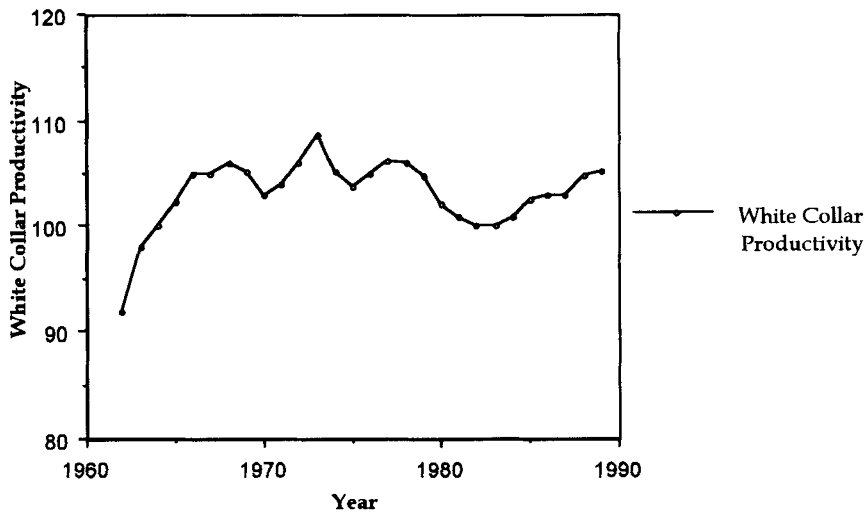



FIG. 6. White collar productivity appears to have stagnated. [Data from Roach (1991).]

to clarify the principal issues surrounding IT and productivity. We assimilate the results of a computerized literature surrounding IT and productivity. We assimilate the results of a computerized literature search of 30 leading journals in information systems and economics.[8] In addition, many of the leading researchers in this area identified recent research that has not yet been published.

The productivity of IT can be measured using data on the whole economy, on specified industries, or on individual firms. In the 1980s and early 1990s, disappointment in information technology was chronicles in articles disclosing broad negative correlations with economy-wide productivity. Several econometric estimates also indicated low IT capital productivity in a variety of manufacturing and service industries. More recently, researchers began to find positive relationships between IT investment and various measures of economic performance at the level of individual firms. The principal empirical research studies of IT and productivity are listed in Table I.

## 2. Research on Economy-wide Productivity and Information Worker Productivity

Economists have been unable to explain the slowdown in measured productivity growth that began in the early 1970s. Labor productivity grew about 2.5% per year from 1953 to 1968, but dropped to about 0.7% per year from 1973 to 1979. Multifactor productivity growth declined from 1.75% a year to 0.32% (Baily, 1986b). Even after accounting for factors such as the oil price shocks, changes in the quality of the labor force, and potential measurement errors, most researchers still find an unexplained residual drop in productivity that roughly coincides with the rapid increase in the use of information technology.

Jorgenson and Stiroh's (1995) more recent growth accounting confirms this correlation. They calculate that average multifactor productivity growth dropped from 1.7% per year for the 1947–73 period to about 0.5% for the

[8] The journals searched were *American Economic Review, Bell (Rand) Journal of Economics, Brookings Papers on Economics and Accounting, Econometrica, Economic Development Review, Economica, Economics of Innovation and New Technology, Economics Journal, Economist (Netherlands), Information Economics & Policy, International Economics Review, Journal of Business Finance, Communications of the ACM, Database, Datamation, Decision Sciences, Harvard Business Review, IEEE Spectrum, IEEE Transactions on Engineering Management, IEEE Transactions on Software Engineering, Information & Management, Interfaces, Journal of MIS, Journal of Systems Management, Management Science, MIS Quarterly, Operations Research,* and *Sloan Management Review.* Articles were selected if they indicated an emphasis on computers, information systems, information technology, decision support systems, expert systems, or high technology combined with an emphasis on productivity.

Table I

Principal Empirical Studies of IT and Productivity

| | Cross-sector | Manufacturing | Services |
|---|---|---|---|
| Aggregate-level studies (economy-wide and industry-level) | Jonscher (1983, 1994)<br>Baily (1986b), Baily & Chakrabarti (1988), Baily & Gordon (1988)<br>Roach (1987, 1989b)<br>Brooke (1992)<br>Lau & Tokutsu (1992)<br>Oliner & Sichel (1994)<br>Jorgenson & Stiroh (1995) | Morrison & Berndt (1991)<br>Berndt *et al.* (1992)<br>Berndt & Morrison (1995)<br>Siegel & Griliches (1992)<br>Siegel (1994) | Brand & Duke (1982)<br>Baily (1986a)<br>Roach (1987, 1989a, 1991) |
| Micro-level studies (firm and workers) | Osterman (1986)<br>Dos Santos *et al.* (1993)<br>Krueger (1993)<br>Brynjolfsson & Hitt (1994)<br>Hitt & Brynjolfsson (1994)<br>Lichtenberg (1995)<br>Brynjolfsson & Hitt (1996) | Loveman (1994)<br>Weill (1992)<br>Dudley & Lasserre (1989)<br>Barua *et al.* (1991)<br>Brynjolfsson & Hitt (1993, 1995, 1996) | Cron & Sobol (1983)<br>Pulley & Braunstein (1984)<br>Bender (1986)<br>Bresnahan (1986)<br>Franke (1987)<br>Strassmann (1985, 1990)<br>Harris & Katz (1991)<br>Parsons *et al.* (1990)<br>Diewert & Smith (1994) |

1973–92 period. At the same time, OCAM capital as a percentage of all producers' durable equipment (PDE) investment rose from about 0.5% in the 1960s to 12% in 1993. A broader category of IT capital, information processing equipment (IPE), now constitutes 34.2% of all PDE investment (Table II). Although productivity growth, especially in manufacturing, has rebounded somewhat recently, the overall negative correlation between productivity and the advent of computers underlies many arguments that information technology has not helped the United States' productivity and that information technology investments have been counterproductive. [see, for example, Baily (1986b)].

This argument was made more explicitly by Stephen Roach (1987, 1988) who focused on the productivity of information workers. In the past, office work was not very capital intensive, but recently the level of IT capital per "white collar" information worker has approached that of production capital per "blue collar" production worker. Concurrently, the ranks of information workers have ballooned and the ranks of production workers have shrunk. Roach shows that output per production worker grew by 16.9% between the 1970s and 1986, while output per information worker decreased by 6.6%. He concludes: "America's productivity shortfall [is] concentrated in that portion of the economy that is the largest employer of white-collar workers and the most heavily endowed with high-tech capital." Roach's analysis provided quantitative support for widespread reports of low office productivity.[9]

But the economy's productivity record in the 1970s and 1980s cannot be blamed on the investment in information technology; many other factors also affect productivity and, until recently, computers were not a major share of the economy. Consider an order of magnitude estimate. In 1992, IT capital stock (OCAM) was equal to about 10% of GDP (with a base year of 1987). If, hypothetically, IT's marginal product were 50% (exceeding the return to most other capital investments), then the level of gross domestic product (GDP) would be directly increased about 5% (10% × 50%) because of the current stock of IT. However, information technology capital stock did not jump to its current level in 1 year; rather, the increase must be spread over about 30 years, suggesting an average *annual* contribution to aggregate GDP growth of 0.15%. This contribution would be very difficult to isolate because so many other factors affected GDP, especially in the relatively turbulent 1970s and 1980s. Indeed, if the marginal product of IT

[9] For instance, Lester Thurow (1987) has noted that "the American factory works, the American office doesn't," citing examples from the auto industry indicating that Japanese managers are able to get more output from blue collar workers (even in American plants) with up to 40% fewer managers.

TABLE II

SELECTED INVESTMENT COMPONENTS IN 1970 AND 1993 (CURRENT DOLLARS)

| Item \ Year | Investment 1970 ($ Billion) | Percentage of: Fixed Investment (%) | Percentage of: PDE (%) | Investment 1993 ($ Billion) | Percentage of: Fixed Investment (%) | Percentage of: PDE (%) |
|---|---|---|---|---|---|---|
| Fixed investment | 148.1 | 100.0 | | 866.7 | 100.0 | |
| Nonresidential investment | 106.7 | 72.05 | | 616.1 | 71.1 | |
| PDE (nonresidential) | 66.4 | 44.83 | 100.00 | 442.7 | 51.1 | 100.0 |
| information processing | 14.3 | 9.66 | 21.54 | 151.5 | 17.5 | 34.2 |
| OCAM | 4.1 | 2.77 | 6.17 | 53.7 | 6.2 | 12.1 |
| Computer equipment | 2.7 | 1.82 | 4.07 | 47.0 | 5.4 | 10.6 |
| Industrial equipment | 20.2 | 13.64 | 30.42 | 96.7 | 11.2 | 21.8 |
| Transportation | 16.1 | 10.87 | 24.25 | 104.2 | 12.0 | 23.5 |

*Sources:* Survey of Current Business, July 1994; U.S. Bureau of Economic Analysis (1992, Vol. 2. Tables 5.4 and 5.8); adapted from Oliner and Sichel (1994).

*Note:* Information processing equipment: OCAM (office, computing and accounting machinery), communication equipment, and scientific and engineering equipment.

capital were anywhere from 0 to +65%, it would still not have affected aggregate GDP growth by more than about 0.2% per year.[10] More comprehensive growth accounting exercises confirm this estimate (see Section 5).

Thus, very large changes in capital stock are needed to change total output measurably, although computers may have had significant effects in specific activities, such as transaction processing, and on other characteristics of the economy, such as employment shares, organizational structure, and product variety. However, as the information technology stock continues to grow and the share of the total economy accounted for by computers becomes substantial, we should begin to find changes in the level of aggre-

[10] Each white collar worker is endowed with about $10,000 in IT capital, which at a 50% ROI, would increase his or her total output by about $5000 per year over precomputer levels of output. In contrast, it costs about $100,000 or so in salary and overhead to employ a white collar worker.

gate GDP.[11] Some recent studies report a high contribution of computers to GDP growth [see, for example, Jorgenson and Stiroh (1995)].

Just as it is hard to isolate information technology's effect on the economy, white collar productivity cannot be directly inferred from the number of information workers per unit of output. For instance, if a new delivery schedule optimizer allows a firm to substitute one clerk for two truckers, the increase in the number of white collar workers is evidence of an *increase* in their relative productivity as well as the firm's productivity. Osterman (1986) suggests that such efficiency improvements can explain why firms often hire more clerical workers after they introduce computers, and Berndt *et al.* (1992) confirm that information technology capital is, on average, a complement for white collar labor and is correlated with fewer blue collar workers. Berman *et al.* (1994) also find that the "increased use of nonproduction workers is strongly correlated with investment in computers and R&D." Unfortunately, it is exceedlingly difficult to measure directly the productivity of office workers.

Independent of its implications for productivity, growth in the white collar workforce cannot be attributed solely to information technology. Although almost half of workers now use computers in their jobs (Katz and Kreuger, 1994), the ranks of information workers began to surge even before the advent of computers (Porat, 1977). In fact, Jonscher (1994) argues that the increased *demand* for information technology created economies of scale and learning in the computer industry, thereby reducing the cost of computers.

In line with this argument, the unbalanced growth hypothesis may provide a sensible economic explanation.[12] Economic growth may slow down because of intrinsically slow technical progress in the white colalr sector, since it is less subject to automation. Then why is the white collar sector's share in the economy growing? One possible answer is the higher income elasticity (and lower price elasticity) of demand for services of this sector. As income

[11] An important study of computer-using workers by Krueger (1993) indirectly supports this view. He found that computer-using workers earned wages 10 to 18% higher than nonusers. In 1984, 24.6% of workers were using computers at work. By 1989, this number had grown to 37.4%. Katz and Krueger (1994) also report that this share of workers had risen to 47% by 1993. Assuming that workers are paid according to their productivity, this implies that computers at work increase GDP level by 3% ($3\% = 0.7 \times 0.1 \times 37.4\%$, 0.1 is the excess marginal product, and 0.7 is the labor share of GDP). Although this number is not sufficient to compensate for the annual 1% productivity slowdown after the early 1970s, it indicates that information technology may boost office worker productivity.

[12] See, for example, Baumol (1967), and Baumol *et al.* (1985).

increases, people demand more services of white collar sectors. Thus, even if information technology does not add to productivity, companies in developed countries may be forced to invest in it. Since it is difficult to measure white collar sector output, the story becomes complicated. Companies invest in computers to produce "unmeasurables," as argued in Griliches (1994). In short, the increased IT use may not be a source of the productivity slowdown, but simply a response to the overall transformation of the economy. Furthermore, the main benefits from using computers appear to be in areas such as improved quality, variety, timeliness, and customization, which are not well-measured in official productivity statistics (Brynjolfsson, 1994).

## 3. Industry-Level Studies of Information Technology Productivity

The preceding section has shown that contrasting the economy-wide productivity slowdown with increasing IT investment is an obtuse approach, because so many other factors may intervene. Going down to the firm level helps to control many problems that arise from aggregation, but it is often difficult to find data representative for the whole economy. Industry-level studies may provide a middle-of-the-road alternative. Table III summarizes some of the important studies. We start with studies on service sectors.

It has been widely reported that most of the productivity slowdown is concentrated in the service sector (Schneider, 1987; Roach, 1987, 1991). Before about 1970, service and manufacturing productivity growth rates were comparable, but since then the trends have diverged significantly.[13] Meanwhile services have dramatically increased as a share of total employment and, to a lesser extent, as a share of total output. Because services use up to 80% of computer capital (Table IV), the slow growth of productivity in the service sector has been taken as indirect evidence of poor information

[13] According to government statistics, from 1953 to 1968, labor productivity growth in services averaged 2.56% versus 2.61% in manufacturing. For 1973 to 1979, the figures are 0.68% versus 1.53%, respectively (Baily, 1986b). However, Gordon and Baily (1989) and Griliches (1994, 1995) suggest that measurement errors in U.S. statistics systematically understate service productivity growth relative to manufacturing. More recently, computers definitely have caused some divergence in the statistics on manufacturing and service productivity, but for a very different reason. Because of the enormous quality improvements attributed to the computers, the nonelectrical machinery category (containing the computer-producing industry) has shown tremendous growth. Partly, as a result, overall manufacturing productivity growth has rebounded from about 1.5% in the 1970s to 3.5% in the 1980s.

TABLE III

INDUSTRY-LEVEL STUDIES

| Study | Sector | Data Source | Findings |
|---|---|---|---|
| Brand (1982) | Services | BLS[a] | Productivity growth of 1.3%/yr in banking |
| Roach (1987, 1989a, 1991) | Services | Principally BLS, BEA[a] | Vast increase in IT capital per information worker and a decrease in measured output per worker |
| Morrison & Berndt (1991) | Manufacturing | BEA | IT marginal benefit is 80 cents per dollar invested |
| Berndt *et al.* (1992), Berndt & Morrison (1995) | Manufacturing | BEA, BLS | IT not correlated with higher productivity in most of industries, but correlated with more labor |
| Siegel & Griliches (1992) | Manufacturing | Multiple government sources | IT-using industries tend to be more productive; government data are unreliable |
| Siegel (1994) | Manufacturing | Multiple government sources | A multiple-indicators and multiple-causes model captures significant MFP effects of computers |

[a] BLS, U.S. Bureau of Labor Statistics; BEA, U.S. Bureau of Economic Analysis.

TABLE IV

INVESTMENT IN COMPUTERS (OCAM) IN THE U.S. ECONOMY (PERCENTAGE OF TOTAL IN CURRENT DOLLARS)

| Industry | 1979 (%) | 1989 (%) | 1992 (%) |
|---|---|---|---|
| Agriculture | 0.1 | 0.1 | 0.1 |
| Mining | 2.4 | 1.1 | 0.9 |
| Manufacturing | 29.4 | 20.3 | 20.2 |
| Construction[a] | 0.1 | 0.3 | 0.2 |
| Nonservice Total | 32.0 | 21.8 | 21.4 |
| Transportation | 1.3 | 2.0 | 1.0 |
| Communication | 1.5 | 1.4 | 1.5 |
| Utilities | 1.2 | 2.8 | 2.8 |
| Trade[a] | 19.9 | 16.3 | 20.0 |
| Finance[a] | 32.5 | 38.7 | 37.8 |
| Other Services[a] | 11.6 | 17.0 | 13.9 |
| Services Total | 68.0 | 78.2 | 78.6 |
| Unmeasurable Sectors[a] | 64.1 | 72.3 | 71.9 |
| Plus consumer and government purchases | 67.7 | 77.6 | 77.0 |
| Unmeasurable sector output | 63 | 69 | 70 |

*Source:* BEA, adapted from Griliches (1995).
[a] Unmeasurable sectors: construction, trade, finance and other services; in these sectors outputs are difficult to measure, relative to measurable sectors.

technology productivity. Roach's research (1987, 1989a, 1989b, 1991) on white collar productivity, discussed earlier, focused principally on IT's performance in the service sector. He argued that IT is an effective substitute for labor in most manufacturing industries, but has been associated with bloating white collar employment in services, especially finance. He attributed this to relatively keener competitive pressures in manufacturing, and he foresees a period of belt-tightening and restructuring in services as they begin to face international competition.

However, studies of manufacturing also found evidence that computers may not increase productivity. Berndt and Morrison analyzed a broader data set from the U.S. Bureau of Economic Analysis (BEA) that encompasses the whole U.S. manufacturing sector. In their first paper (Morrison and Berndt, 1991), they examined a series of parameterized models of production and found evidence that every dollar spent on IT delivered, on average, only about $0.80 of value on the margin, indicating a general overinvestment in IT. Their later paper (Berndt and Morrison, 1995) examined broad correlations of IT investment with labor productivity and multifactor productivity. This approach did not find a significant difference between the productivity of IT capital and other types of capital for a majority of the 20 industry categories examined. They did find that investment in IT was correlated with increased demand for skilled labor.

Siegel and Griliches (1992) used industry and establishment data from a variety of sources to examine several possible biases in conventional productivity estimates. They found a positive simple correlation between an industry's level of investment in computers and its multifactor productivity growth in the 1980s. They did not examine more structural approaches, in part because of troubling concerns about the reliability of the data and government measurement techniques. Their findings contrast with those of Berndt and Morrison (1995). However, Berndt and Morrision (1995) also document positive correlations between IT capital and some measures of economic performance in the specifications where cross-sectional effects were emphasized. In addition, Berndt and Morrison's level of aggregation (two-digit SIC code) is broader than that of Siegel and Griliches' (four-digit SIC code).

Many researchers working on industry-level data express concerns about data problems, which are often caused by aggregation. For example, the BEA data are mainly used for industry-level analyses, but it is subject to subtle biases due to the techniques used to aggregate and classify establishments. One of Siegel and Griliches' (1992) principal conclusions was that "after auditing the industry numbers, we found that a non-negligible number of sectors were not consistently defined over time."

Siegel (1994) attempts to tackle the data problems that arise from two possible sources of measurement error. The first kind of error occurs when computer price and quantity are measured with error. The second source of error is more subtle: Firms invest in computers not only for cost reduction but also for quality improvement.[14] Because the quality improvement is not fully taken into account in traditional statistics, the errors in output measurement are correlated with computer investment. These two kinds of errors cause bias and inefficiency in estimation. After controlling these errors using a "multiple-indicators and multiple-causes" model, Siegel found a significant positive relationship between multifactor productivity growth and computer investment. He also found that computer investment is positively correlated with both product quality and labor quality, a result that is consistent with Brynjolfsson (1994), Berndt and Morrison (1995), and Berman *et al.* (1994).

[14] See also Brynjolfsson (1994).

## 4. Firm-Level Studies of Information Technology Productivity

During the past 10 years, many studies examined the relationship between firms' IT investment and their performance. Interestingly, studies that have used larger and more recent data sets have found evidence that IT positively affects firm performance. Research results in manufacturing often show stronger effects than studies of services, probably because of better measurement.

### 4.1 Service Sector Studies

Strassmann (1985) reports disappointing evidence in several studies (see Table V for a list of service sector studies). In particular, he found that there was no correlation between IT and return on investment in a sample of 38 service sector firms: Some top performers invest heavily in IT, others do not. In his later book (1990), Strassmann concludes that "there is no relation between spending for computers, profits and productivity."

Several studies have examined IT's impact on the performance of financial services firms. Parsons *et al.* (1990) estimated a production function for banking services in Canada. They found that the impact of IT on multifactor productivity was quite low between 1974 and 1987. They speculated that IT has positioned the industry for greater growth in the future. Similarly, Franke (1987) found that IT was associated with a sharp drop in capital productivity and stagnation in labor productivity, but remained optimistic about the future potential of IT, citing the long time lags associated with previous "technological transformations" such as the conversion to steam power. In contrast, Brand and Duke (1982) used Bureau of Labor Statistics (BLS) data and techniques and found that moderate productivity growth had already occurred in banking.

Harris and Katz (1991) and Bender (1986) examined data on the insurance industry from the Life Office Management Association Information Processing Database. They found positive but sometimes weak relationships between IT expense ratios and various performance ratios. Alpar and Kim (1991) studied 759 banks and found that a 10% increase in IT capital is associated with a 1.9% decrease in total costs. Several case studies of IT's impact on performance have also been done. Weitzendorf and Wigand (1991) developed a model of information use in two service firms; and Pulley and Braunstein (1984) studied an information services firm and found an association between IT investment and increased economies of scope.

Estimating a production function, Brynjolfsson and Hitt (1993) found that for the service firms in their sample, gross marginal product averaged

Table V

Studies of Firms in the Service Sector

| Study | Data Source | Findings |
|---|---|---|
| Pulley & Braunstein (1984) | An info service firm | Significant economies of scope |
| Clarke (1985) | Case study | Major business process redesign needed to reap benefits in investment firm |
| Strassmann (1985, 1990) | Computerworld survey of 38 companies | No correlation between various IT ratios and performance measures |
| Bender (1986) | LOMA insurance data on 132 firms | Weak relationship between IT and various performance ratios |
| Franke (1987) | Finance industry data | IT was associated with a sharp drop in capital productivity and stagnant labor productivity |
| Harris & Katz (1991) | LOMA insurance data for 40 | Weak positive relationship between IT and various performance ratios |
| Noyelle (1990) | U.S. and French industry | Severe measurement problems in services |
| Parsons *et al.* (1990) | Internal operating data from two large banks | IT coefficient in translog production function small and often negative |
| Alpar and Kim (1991) | Large number of banks | IT is cost saving, labor saving, and capital using |
| Weitzendorf & Wigand (1991) | Interviews at two companies | Interactive model of information use |
| Diewert & Smith (1994) | A large Canadian retail firm | Multifactor productivity grows 9.4% per quarter over six quarters |
| Brynjolfsson & Hitt (1995) | IDG, Compustat, BEA | Marginal products of IT do not differ much in services and in the manufacturing; firm effects account for 50% of the marginal product differential |

more than 60% per year. Their 1995 study reports that IT contributes as much output in the service sector as in the manufacturing sector (Brynjolfsson and Hitt, 1995). Because they used firm-level data, this result suggests that the productivity "slowdown" in the service sector may be an artifact of the mismeasurement of output in aggregate data sets. Indeed, even when firms were classified into "measurable" and "unmeasurable" sectors as defined by Griliches (1994), no noticeable difference in IT productivity between the sectors was found using this firm-level data.

Diewert and Smith (1994) provide an interesting case study of a large Canadian retail distribution firm. They found that the firm experienced an astounding 9.4% quarterly multifactor productivity growth for six consecutive quarters starting at the second quarter of 1988. They argue that "these large productivity gains are made possible by the computer revolution which allows a firm to track accurately its purchase and sales of inventory items and to use the latest computer software to minimize inventory holding costs."

Measurement problems are more acute in services than in manufacturing, partly because many service transactions are idiosyncratic, and therefore not amenable to statistical aggregation. Even when data are abundant, classifications sometimes seem arbitrary. For instance, in accordance with one standard approach, Parsons *et al.* (1990) treat *time* deposits as inputs into the banking production function and *demand* deposits as outputs. The logic for such decisions is sometimes tenuous, and subtle changes in deposit patterns or classification standards can have disproportionate impacts.

The importance of variables other than IT is also particularly apparent in some of the service sector studies. In particular, researchers and consultants have increasingly emphasized the need to reengineer work when introducing major IT investments.[15] As Wilson (1995) suggests, it would be interesting to know whether reengineering efforts are the main explanation for Brynjolfsson and Hitt's (1993, 1995) findings that IT is correlated with increased output. A recent survey found that, in fact, firms that had reengineered were significantly more productive than their competitors (Brynjolfsson, 1994).

### 4.2 Studies of Manufacturing Sector and Cross-Sector Studies

There have been several firm-level studies of IT productivity in the manufacturing sector. Some of the important results are summarized in

[15] See, for example, Davenport (1990), Davenport and Short (1993), Hammer (1990), Hammer and Champy (1993), and Champy (1995).

Table VI. A study by Loveman (1994) provided some of the first econometric evidence of an IT productivity shortfall, when he examined data from 60 business units using the Management Productivity and Information Technology (MPIT) subset of the Profit Impact of Market Strategy (PIMS) database. As is common in productivity literature, he used an ordinary least squares regression and assumed that production functions could be approximated by a Cobb–Douglas function. Loveman estimated that the contribution of information technology capital to final output was approximately zero over the 5-year period he studied in almost every subsample. His findings were fairly robust to a number of variations on his basic formulation.

Barua *et al.* (1991) traced Loveman's results back a step by looking at IT's effect on intermediate variables such as capacity utilization, inventory turnover, quality, relative price, and new product introduction. Using the same data set, they found that IT was positively related to three of these five intermediate measures, but that the effect was generally too small to affect final output measurably. Dudley and Lasserre (1989) also found econometric support for the hypothesis that better communication and information reduce the need for inventories, without explicitly relating this to bottom-line performance measures. Using a different data set, Weill (1992) disaggregated IT by use and found that significant productivity could

TABLE VI

STUDIES OF MANUFACTURING FIRMS AND CROSS-SECTOR FIRMS

| Study | Data Source | Findings |
|---|---|---|
| Loveman (1994) | PIMS/MPIT | IT investments added nothing to output |
| Dudley & Lasserre (1989) | U.S. and Canadian Aggregate Data | IT and communication reduces inventories |
| Weill (1992) | Valve manufacturers | Contextual variables affect IT performance; transaction processing IT produce positive results |
| Barua *et al.* (1991) | PIMS/MPIT | IT improved intermediate outputs, if not necessarily final output |
| Brynjolfsson & Hitt (1993) | IDG; Compustat: BEA | The gross marginal product of IT capital is over 50% per year in manufacturing |
| Brynjolfsson & Hitt (1995) | IDG; Compustat: BEA | Firm effects account for half of the productivity benefits of earlier study |
| Lichtenberg (1995) | IDG; Informationweek (cross sector) | IT has excess return; IT staff's substitution effect is large |
| Kwon & Stoneman (1995) | UK survey | New technology adoption, especially computer use, has a positive impact on output and productivity |

be attributed to transactional types of information technology (e.g., data processing), but was unable to identify gains associated with strategic systems (e.g., sales support) or informational investments (e.g., e-mail infrastructure).

In a series of studies utilizing large firm-level surveys by International Data Group (IDG), Brynjolfsson and Hitt report that IT improves productivity. Their 1993 study found that while the gross marginal product of noncomputer capital ranges from 4.14 to 6.86%, that of computer capital averages 56 to 68%. The results of this and their later study (Hitt and Brynjolfsson, 1994) imply that the following three null hypotheses can be rejected:

H1: IT capital has a *zero gross* marginal product.
H2: IT capital has *zero net* marginal benefit, after all costs have been subtracted.
H3: IT capital's marginal product is *not different* from that of other capital.

Their point estimates of gross marginal products indicate that at the margin computer capital generates 10 times more output than other capital of equal value. Brynjolfsson and Hitt (1995) show that up to half of the excess returns imputed to IT could be attributed to firm-specific effects.

If gross marginal product of information technology capital is really so large, what friction or market failure prevents firms from investing in more computers, until the marginal products of all capital goods become equal?[16] One reason is that computer capital has a higher user cost. According to Oliner and Sichel (1994), from 1970 to 1992 the user cost of computer capital averaged 36.6% per year, while that of other types of capital was 15.4%.[17] The remaining portion of the answer may come from adjustment or hidden costs of information technology investment, such as the complementary organizational investments required to realize the benefits of IT.[18]

Lichtenberg (1995) confirms the results of Brynjolfsson and Hitt, using similar data and methods. He also analyzes *Informationweek* survey data and uncovers essentially the same results. His formal tests reject the above null hypotheses. Importantly, Lichtenberg extends his study to report the

[16] See, for example, Robert J. Gordon's comment on Oliner and Sichel (1994).

[17] The differential is largely due to the rapid decline in computer prices.

[18] Take 60% per year as Brynjolfsson and Hitt's (1993) estimate of gross marginal product of information technology capital. IT's marginal product is more than 50% higher than that of other types of capital. About 20% (36.6–15.4%) is explained by the user costs of capital differential. Because the unexplained portion is large, we may expect a considerable amount in adjustment costs when implementing IT investment—annual 30% of computer capital stock.

marginal rate of substitution between IT and non-IT workers. At the sample mean, one IT worker can apparently be substituted for six non-IT workers.

Research in manufacturing generally finds higher returns to IT investment than in the services, probably because of better measurement. Yet the MPIT data, which both Loveman (1994) and Barua *et al.* (1991) use, must be scrutinized. Although the point estimates for IT's contribution were quite low, the standard errors were very high so that the 95% confidence interval often exceeded ±200% for Loveman's estimates. These studies may also be unrepresentative, since the period covered by the MPIT data, 1978–83, was unusually turbulent.

The IDG data set, which is among the largest data sets used in this research area, substantially mitigates data problems, although it contains data on large firms only, and so may not be a representative random sample. Indeed, Brynjolfsson and Hitt (1993) attribute the statistical significance of their findings partly to the large size of the IDG data set, which enables them to more precisely estimate returns for all factors. Utilizing comprehensive surveys of the UK engineering industry undertaken in 1981, 1986, and 1993, Kwon and Stoneman (1995) also find that the use of computers and numerical control machines has increased output and productivity.

## 5. Contribution to Consumer Surplus and Economic Growth

Some researchers have identified sizable contributions of IT to consumer surplus and to economic growth. Some important studies are summarized in Table VII. Growth accounting and consumer surplus analysis are techniques to identify and measure "pecuniary externalities," which Griliches (1992, 1994) distinguishes from "non-pecuniary externalities of spill-overs."

Pecuniary externalities arise when the price of some input declines. For example, when computer prices are declining exogenously, profit-maximizing firms substitute computer systems for other input factors, such as labor or warehouse space. Lowered prices of computers and other inputs shift marginal cost curves downward. These marginal cost curves result in higher output and lower prices. The output increase is a measure of the pecuniary externality; the benefits created by the computer sector are reflected in greater output of *computer-using* industries. A second measure of the pecuniary externality is consumer surplus. As computer prices fall, many firms and customers that could not afford computers become able to purchase them, whereas the customers who were willing to pay higher prices enjoy a windfall of price reduction.

TABLE VII

STUDIES ON CONTRIBUTION TO CONSUMER SURPLUS AND ECONOMIC GROWTH

| Study | Data Source | Findings |
|---|---|---|
| Bresnahan (1986) | Financial service firms | Large gains in imputed consumer welfare |
| Lau & Tokutsu (1992) | Multiple government sources | Computer capital contributes half of output growth |
| Brynjolfsson & Hitt (1994) | IDG,[a] Compustat | Growth contribution of computers is 1% per year among 367 U.S. large firms |
| Oliner & Sichel (1994) | Principally BEA[a] | Growth contribution of computers is 0.16–0.38% per year varying by different assumptions |
| Jorgenson & Stiroh (1995) | Principally BEA | Growth contribution of computers for the 1979–92 period is 0.38–0.52% per year |
| Brynjolfsson (1995) | BEA | $70 billion consumer surplus is generated annually in the late 1980s. |

[a] IDG, International Data Group; BEA, U.S. Bureau of Economic Analysis.

Pecuniary externalities directly increase labor productivity, yet they do not necessarily increase multifactor productivity. Pecuniary externalities do not change the production function, rather they change the input mix. In contrast, nonpecuniary externalities, or spill-overs, arise from technical change; people may have found smarter ways of making goods and services using information technology.[19] The production possibility frontier shifts out; both labor productivity and multifactor productivity should go up.

Bresnahan (1986) estimated the benefits to consumers of declining computer prices. Using the hedonic price index method,[20] he calculates that the consumer surplus was five or more times that of computer expenditures in the late 1960s financial sector. Adopting similar assumptions, Brynjolfsson (1995) estimates that, in 1987, between $69 billion and $79 billion consumer surplus was generated by $25 billion in expenditures on information technology capital.

Now we turn to several growth accounting results. Jorgenson and Stiroh's (1995) comprehensive growth accounting found that from 1979 to 1985 computers and peripherals contributed to output growth by 0.52% per year, and that from 1985 to 1992, the contribution was 0.38% per year (see Table

[19] Bresnahan and Trajtenberg (1995) argue that "general purpose technologies," like computers, engender waves of smaller and complementary innovations. This creates the potential for positive externalities from IT, and thus the possibility that IT investment is too low, compared to the socially optimal level.

[20] The hedonic price index method is an attempt to incorporate quality changes when constructing price indices using the regression technique. See Chapter 4 in Berndt (1991).

VIII).[21] Because they assume that computers maintain their full ability until retirement, their estimation of computer capital's contribution becomes larger than that of Oliner and Sichel (1994).

Oliner and Sichel (1994) carefully examine how the various excess return hypotheses of computer capital affect growth. As a baseline they estimate that the contribution of computer capital to output growth is 0.16% per year for the 1970–92 period. Using Romer's (1986, 1987) assumption that physical capital provides a positive externality, the contribution goes up to 0.32%. Brynjolfsson and Hitt's (1993) higher estimate for the return on computer capital raises the contribution to 0.35%. They also try to incorporate Alan Krueger's (1993) result of return on workers' computer use. If the return is equal to the difference in the marginal product between computer-using workers and nonusing workers, the contribution is 0.38%. Oliver and Sichel claim that an annual contribution of up to 0.38% is not large enough to offset the approximately 1% drop in output growth since the 1970s.[22]

The following rough calculation may provide some intuition about the size of the contribution of computers to national output. From Jorgenson and Stiroh (1995), we take the simple average contribution for the 1979–92 period or 0.45%. We compare it with the 0.72% contribution of other capital. The share of computers in total capital stock was 1.6% in 1993, implying that 1 unit of computer capital contributes as much to the growth of output as 98 units of other forms of capital. In 1993, GDP grew by $173 billion.[23] Computers contributed $29 billion; other capital contributed $46 billion. The unexplained residual (MFP) contribution is $40 billion. A rough estimate shows that the implicit marginal product of computer capital in Jorgenson and Stiroh's study is more than 60%.[24]

Using data from 367 large firms that together generated $1.8 trillion in output per year from 1982 to 1992, Brynjolfsson and Hitt (1994) provide

[21] The contribution dropped because the growth rate of real computer capital is lower for the 1979–85 period than for the 1985–92 period; nominal investment of computers did not increase much during the 1985–92 period.

[22] However, an alternative view is that the glass is half-full; Jorgenson calls 0.38% "a pretty hefty contribution" (personal letter, Feb. 7, 1995).

[23] Survey of *Current Business,* March 1994, Table 1-1, nominal dollars.

[24] One of the standard growth accounting assumptions is that factors are paid according to their marginal product. Jorgenson and Stiroh report 0.38% growth contribution for the period 1985–92. The 0.38% is computers' nominal income share times computer capital's growth rate. By their data, we can also estimate computer capital's growth rate during the 1985–87 period (24%). Now computers' nominal income share is equal to (computers capital's marginal product × computer capital/GDP). In 1987, computer capital stock amounted to $113.24 billion and GDP was $4.5399 trillion, thus the implicit marginal product of computers is estimated to 63% = (0.38%)* ($4539.9/$113.24)/(24%).

Table VIII

Growth Rates of Aggregate Output and Contribution of Factors (1947–92)

| | Value Added | | | Growth Contribution | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable Period | Annual Growth | Noncomp Share | Computer Share | Capital | Noncomp Share | Computer Share | Labor | Multifactor Productivity |
| 47–92 | 3.42 | 3.33 | 0.09 | 1.47 | 1.26 | 0.21 | 0.92 | 1.03 |
| 47–53 | 5.46 | 5.46 | 0.00 | 1.92 | 1.92 | 0.00 | 1.26 | 2.27 |
| 53–57 | 2.14 | 2.14 | 0.00 | 1.42 | 1.42 | 0.00 | 0.19 | 0.53 |
| 57–60 | 2.39 | 2.37 | 0.02 | 0.83 | 0.83 | 0.00 | −0.01 | 1.57 |
| 60–66 | 5.38 | 5.30 | 0.08 | 1.46 | 1.36 | 0.10 | 1.44 | 2.48 |
| 66–69 | 2.61 | 2.54 | 0.07 | 1.93 | 1.74 | 0.20 | 1.16 | −0.49 |
| 69–73 | 3.67 | 3.60 | 0.08 | 1.64 | 1.40 | 0.24 | 0.74 | 1.29 |
| 73–79 | 2.63 | 2.50 | 0.12 | 1.45 | 1.19 | 0.26 | 1.28 | −0.10 |
| 79–85 | 2.89 | 2.65 | 0.24 | 1.28 | 0.76 | 0.52 | 0.83 | 0.78 |
| 85–92 | 2.49 | 2.38 | 0.12 | 1.26 | 0.88 | 0.38 | 0.76 | 0.47 |

*Source:* Adapted from Jorgenson and Stiroh (1995).

an interesting growth accounting result. For their sample of firms, IT capital contributes about 1% per annum to output growth—a larger growth contribution than that of ordinary capital in absolute value. Lau and Tokutsu (1992) calculate an even bigger contribution to growth, attributing approximately half of the real output growth (1.5% growth per annum) during the past three decades to computer capital. They also argue that the annual rate of inflation dropped by 1.2% per year because of the rapid decline in computer prices. In line with these studies, Roy Radner suggests that "productivity growth has slowed down for other reasons, unrelated to the IT story. Without IT, things would have been worse, and output growth would have been lower" (Griliches, 1995).

In summary, the weight of evidence from various studies indicates that information technology capital generates billions of dollars annually for the U.S. economy, both in terms of output growth and consumer surplus. Meanwhile, the recent firm-level analyses of Brynjolfsson and Hitt (1993, 1995) and Lichtenberg (1995) have begun to remedy the shortfall of evidence regarding the productivity contribution of IT.

## 6. Conclusion: Where Do We Go from Here?

Sections 2, 3, 4, and 5 reviewed the principal empirical literature on the productivity of information technology. Looking at the simple relationship between the productivity slowdown of the whole U.S. economy and the rapid growth of computer capital is too general an approach. Poor data quality for IT outputs and inputs has exacerbated this problem. Due to the application of improved methodologies and the identification of more reliable and larger data sets, researchers have made some progress with industry-level and firm-level studies. Recently, some researchers have found positive effects of IT. Careful growth accounting exercises and estimation of production and cost functions for specific sectors or industries can provide sharper insights. Consumer surplus analyses are useful exercises for identifying alternative ways to triangulate IT value. These studies suggest that without IT, the U.S. economy would probably be in a worse situation than it is. This section proposes further research questions and methodologies.

The first priority is to improve the data and the measurement techniques. Government statistics, especially in services and for information workers, have not kept up with the growing importance and complexity of these sectors. Therefore, researchers may have to perform their own corrections on the data, turn to private sources of secondary data, or gather data themselves. Researchers should make their data available to other researchers so that a cumulative tradition can be maintained. The studies of Weill

(1992), Dos Santos *et al.* (1993), and Brynjolfsson and Hitt (1993, 1995) are examples of new data identification and development.

One effective way to identify possible gaps in the data is to compare them with the benefits that managers and customers expect from IT, such as quality, timeliness, customer service, flexibility, innovation, customization, and variety. In principle, many of these benefits are quantifiable. In fact, some firms already attempt such an analysis in their capital budgeting and justification processes. In addition, many companies have developed elaborate measurement programs, for example, as part of total quality management. These programs augment or even supersede financial accounting measures and can serve as a foundation for more refined metrics (Kaplan and Norton, 1992).

Many economists also have tried various methods to overcome the shortfall of government statistics, and to incorporate quality changes when estimating price indices. The long history of hedonic price index method is a good example, but some economists argue that even the hedonic method does not capture all the benefits associated with product innovation and differentiation. Trajtenberg (1990) devises a new method of quality-adjusted price index calculation, adopting the discrete choice model.[25] Fisher and Griliches (1995) argue that if new inexpensive (quality-adjusted) goods are introduced and gain market share at the expense of existing goods, the official statistics by the BLS will seriously overestimate inflation.[26] Hausman (1994) also reports a 20 to 25% overestimation of the consumer price index for ready-to-eat cereals, based on his analysis of Apple Cinnamon Cheerios.

Unfortunately, for many services, even basic output measures must be created, because government and accounting data records only inputs. Baily and Gordon (1988) and Noyelle (1990), among others, have done much to improve measurement in areas such as banking and retailing, while relatively good statistics can be compiled from private sources in areas such as package delivery. Unfortunately, the individualized nature of many services defies aggregation. The output of a lawyer, manager, or doctor cannot be extrapolated from the number of meetings attended, memoranda written, or medications provided. The complexity of the "diagnostic-related group" approach to valuing medical care is both a step in the right direction and a testament to these difficulties. A researcher who seeks to measure

[25] For the period of 1973–82, Trajtenberg's price deflator for the computed tomography scanner industry averages minus 55%; in contrast, the hedonic price index shows a 13% decline and government price statistics indicate a 9% increase.

[26] Empirical evidence for their argument is presented in Griliches and Cockburn (1994). They show that the adjusted price index for the cephalexin drug during the 1987–91 period dropped by 30 to 53%; the official figure records a 14% increase.

rigorously the productivity of service industries generally must undertake this detailed work before jumping to conclusions based on input-based statistics. Similarly, disaggregating heterogeneous types of IT by use, as Weill (1992) did in a manufacturing study, can increase the resolution of standard statistical techniques.

Because so many factors affect firm performance, it is generally impossible to distinguish the impact of IT using simple bivariate correlations. It is essential to control for other factors such as other inputs and their prices, the macroeconomic environment, demand schedules for output, and the nature of competition. Because many unobservable factors affect either the whole industry or one firm persistently, examining a panel consisting of both time series and cross-sectional data is the best approach, where feasible.

Importantly, we must remember that our tools are still blunt. Managers do not always recognize this and tend to rely too much on any one study of IT and productivity. While the studies usually state the limitations of the data and methods, sometimes only the surprising conclusions are reported by the media. Because significant investment decisions are based on these conclusions,[27] researchers must be doubly careful to communicate the limitations of their work.

Researchers might also look to business for profitable research questions. A recurrent theme in the business press is the idea that information technology should not so much help us produce more of the same things as allow us to do entirely new things in new ways.[28] For instance, Watts (1986) finds that information technology investments cannot be justified by cost reductions alone, but that instead managers should look to increased flexibility and responsiveness, whereas Brooke (1992) writes that information technology leads to greater variety but lower productivity as traditionally measured. Diewert and Smith's (1994) study makes another interesting point with respect to variety. They show that while IT facilitates great efficiency in inventory management, aggregate inventory level of the U.S. economy did not shrink during the past 40 years, as reported by Blinder and Maccini (1991). Diewert and Smith argue that "a wide spread proliferation of new products into the world economy" results in no macro-level inventory change even when great micro-level improvements have been made.

[27] For instance, the stock prices of major IT vendors appeared to change significantly in response to a *Wall Street Journal* article on IT productivity (Dos Santos *et al.*, 1991).

[28] See, for example, Applegate and Mills (1988), Benjamin *et al.* (1984), Champy (1995), Cecil and Hall (1988), Davenport (1993), Hammer and Champy (1993), Malone and Rockart (1991), Porter and Miller (1985), and Watts (1986).

This literature highlights how difficult and perhaps inappropriate it would be to translate some of the benefits of information technology into quantifiable productivity measures of output. Intangibles such as better responsiveness to customers and increased coordination with suppliers do not always increase the amount or even intrinsic quantity of output, but they do help make sure it arrives at the right time, at the right place, with the right attributes for each customer. Berndt and Malone (1995) suggest that "we need to spend more effort measuring new forms of value—such as capabilities for knowledge creation—rather than refining measures of productivity that are rooted in an Industrial Age mindset."

Just as managers look beyond "productivity" for some of the benefits of IT, so must researchers be prepared to look beyond conventional productivity measurement techniques. For instance, because consumers are generally assumed to be in the best position to assess the utility they gain from their purchases, so researchers might look to IT buyers for an estimate of IT value, as Bresnahan (1986) and Brynjolfsson (1995) did. As another example, if rational investors value both the tangible and intangible aspects of firms' revenue-generating capacity, then changes in stock market value should approximate the true contribution of IT to the firm, not only in cost reductions, but also in increased variety, timeliness, quality, and, in principle, even in the effectiveness of the firm in foreseeing and rapidly adapting to its changing environment.[29] While relying on consumer or stockholder valuations begs the question of actual IT productivity to some extent, at a minimum these measures provide two additional benchmarks that can help triangulate IT value (Hitt and Brynjolfsson, 1994).

While the value of IT remains controversial, it is clear that the measurement problem is becoming more severe. Developed nations are devoting increasing shares of their economies to service- and information-intensive activities for which output measures are poor.[30] The emerging "information age" has promoted a new approach to management accounting (Beniger, 1986; Kaplan, 1989). Similarly, researchers should take the opportunity to rethink how we measure productivity and output.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[29] Unfortunately, stock market valuation also reflects the firm's relative market power, so where IT leads to more efficient markets or greater *customer* bargaining power, the relationship between IT and stock price is ambiguous.

[30] The BEA's SIC codes classify manufacturing in relatively rich detail; only the broadest measures exist for services, which comprise more than 80% of the economy.

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## References

Ahituv, N., and Giladi, N. (1993). Business success and information technology: Are they really related. Proc. 7th Annual Conference of Management IS, Tel Aviv University.

Allen, T. J., and Scott Morton, M. S. (1994). *Information Technology and the Corporation of the 1990s,* Oxford University Press.

Alpar, P., and Kim, M. (1991). A microeconomic approach to the measurement of information technology value. *Journal of Management Information Systems* **7**(2), 55–69.

Alpar, P., and Kim, M. (1990). A comparison of approaches to the measurement of information technology value. Proc. Twenty-Second Hawaii International Conference on System Science, Honolulu, HI.

Applegate, L., Cash, J., and Mills, D. Q. (1988). Information technology and tomorrow's manager. *Harvard Business Review,* November–December, pp. 128–136.

Attewell, P., and Rule, J. (1984). Computing and organizations: What we know and what we don't know. *Communications of the ACM,* **27,** 1184–1192.

Ayres, R. U. (1989). Information, computers, CIM and productivity. Organization for Economic Co-operation and Development Paper (June).

Baily, M. N. (1986a). Taming the information monster. *Bell Atlantic Quarterly,* Summer, pp. 33–38.

Baily, M. N. (1986b). What has happened to productivity growth?" *Science* **234,** 443–451.

Baily, M. N., and Chakrabarti, A. (1988). Electronics and white-collar productivity. In *Innovation and Productivity Crisis,* Brookings Institution, Washington, DC.

Baily, M. N., and Gordon, R. J. (1988). The productivity slowdown, measurement issues and the explosion of computer power. *Brookings Papers in Economic Activity* (2), 347–431.

Bakos, J. Y. (1987). "Inter-organizational information systems: Strategic implications for competition and cooperation." Ph.D. Dissertation, MIT School of Management.

Bakos, J. Y., and Kemerer, C. F. (1992). Recent application of economic theory in information technology research. *Decision Support System* **8,** 365–386.

Banker, R. D., and Kauffman, R. J. (1988). Strategic contributions of information technology: An empirical study of ATM networks. Proc. Ninth International Conference on Information Systems, Minneapolis, Minnesota.

Barua, A., Kriebel, C., and Mukhopadhyay, T. (1991). Information technology and business value: An analytic and empirical investigation. University of Texas at Austin Working Paper (May).

Baumol, W. J. (1967). Macroeconomics of unbalanced growth: The anatomy of urban crisis. *American Economic Review* **57**(3), 415–426.

Baumol, W. J., Blackman, S. A., and Wolff, E. N. (1985). Unbalanced growth revisited: Asymptotic stagnancy and new evidence. *American Economic Review* **74**(4), 806–817.

Bender, D. H. (1986). *Financial Impact of Information Processing.* **3**(2), 22–32.

Beniger, J. (1986). *The Control Revolution.* Harvard University Press, Cambridge, MA.

Benjamin, R. I., Rockart, J. F., Scott Morton, M. S., *et al.* (1984). Information technology: A strategic opportunity. *Sloan Management Review,* Spring, pp. 3–10.

Berman, E., Bound, J., and Griliches, Z. (1994). Changes in the demand for skilled labor within U.S. manufacturing: Evidence form the annual survey of manufacturers. *Quarterly Journal of Economics* **109**(2), 367–397.

Berndt, E. R. (1991). *The Practice of Econometrics: Classic and Contemporary,* Addison-Wesley, Reading, MA.

Berndt, E. R., and Malone, T. W. (1995). Information technology and the productivity paradox: Getting the questions right; guest editor's introduction to special issue. *Economics of Innovation and New Technology* **3,** 177–182.

Berndt, E. R., and Morrison, C. J. (1995). High-tech capital formation and economic performance in U.S. manufacturing industries: An exploratory analysis. *Journal of Econometrics* **65,** 9–43.

Berndt, E. R., and Morrison, C. J. (1991). Computers aren't pulling their weight. *Computerworld,* December 9, pp. 23–25.

Berndt, E. R., Morrison, C. J., and Rosenblum, L. S. (1992). High-tech capital formation and labor composition in U.S. manufacturing industries: An exploratory analysis. National Bureau of Economic Research Working Paper No. 4010 (March).

Blinder, A. S., and Maccini, L. J. (1991). Taking stock: A critical assessment of recent research on inventories. Journal of Economic Perspectives **5,** 73–96.

Brand, H., and Duke, J. (1982). Productivity in commercial banking: Computers spur the advance. *Monthly Labor Review* **105,** 19–27 (December).

Bresnahan, T. F. (1986). Measuring spillovers from technical advance: Mainframe computers in financial services. *American Economic Review* **76**(4).

Bresnahan, T. F., and Trajtenberg, M. (1995). General purpose technologies and aggregate growth. *Journal of Econometrics* **65,** 83–108.

Brooke, G. M. (1992). The economics of information technology: Explaining the productivity paradox. MIT Sloan School of Management Center for Information Systems Research Working Paper No. 238 (April).

Brynjolfsson, E. (1995). Some estimates of the contribution of information technology to consumer welfare. MIT Sloan School of Management Working Paper (August).

Brynjolfsson, E. (1994). Technology's true payoff. *Informationweek,* October 10, pp. 34–36.

Brynjolfsson, E. (1993). The productivity paradox of information technology: Review and assessment. *Communications of ACM* **36**(12), 67–77.

Brynjolfsson, E., and Hitt, L. (1996). Paradox lost? Firm-level evidence on the returns to information systems spending. *Management Science* (April).

Brynjolfsson, E., and Hitt, L. (1995). Information technology as a factor of production: The role of differences among firms. *Economics of Innovation and New Technology* **3,** 183–199.

Brynjolfsson, E., and Hitt, L. (1994). Computers and economic growth: Firm-level evidence. MIT Sloan School of Management Working Paper No. 3714 (August).

Brynjolfsson, E., and Hitt, L. (1993). Is information systems spending productive? New evidence and new results. Proc. 14th International Conference on Information Systems, Orlando, FL.

Brynjolfsson, E., Malone, T., Gurbaxani, V., and Kambil, A. (1991). Does information technology lead to smaller firms? *Management Science* **40**(12), 1628–1644.

Champy, J. (1995). *Reengineering Management,* HarperBusiness, New York.

Cecil, J. L., and Hall, E. A. (1988). When IT really matters to business strategy. *McKinsey Quarterly,* Autumn, p. 2.

Chismar, W. G., and Kriebel, C. H. (1985). A method for assessing the economic impact of information systems technology on organizations. Proc. Sixth International Conference on Information Systems, Indianapolis, IN.

Clarke, R. F. (1985). "The application of information technology in an investment management firm." Masters Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Clemens, E. K. (1991). Evaluation of strategic investment in information technology. *Communications of the ACM* **34**(1), 22–36.

Cooper, R. B., and Mukhopadhyay, T. (1990). Research in MIS effectiveness: A microeconomic production view. Carnegie Mellon University Working Paper.

Cron, W. L., and Sobol, M. G. (1983). *The Relationship Between Computerization and Performance: A Strategy for Maximizing the Economic Benefits of Computerization.* Vol. 6, 171–181.

Crowston, K., and Malone, T. W. (1988). Information technology and work organization. Chapter 49 in *Handbook of Human-Computer Interactions* (M. Helander, Ed.). Elsevier Science, Amsterdam, pp. 1051–1070.

Crowston, K., and Treacy, M. E. (1986). Assessing the impact of information technology on enterprise level performance. MIT Center for Information Systems Research Working Paper No. 143 (October).

Curley, K. F., and Pyburn, P. J. (1982). Intellectual technologies: The key to improving white-collar productivity. *Sloan Management Review,* Fall, pp. 31–39.

Davenport, T. H. (1993). *Process Innovation: Reengineering Work through Information Technology.* Harvard Business School Press, Boston.

Davenport, T. H. and Short, J. (1990). The new industrial engineering: Information technology and business redesign. *Sloan Management Review* **31**(4), 11–27.

David, P. A. (1990). The dynamo and the computer and dynamo: A historical perspective on the modern productivity paradox. *American Economic Review* **80**(2), 355–361.

Denison, E. E. (1989). Estimates of productivity change by industry, an evaluation and an alternative. Brookings Institution, Washington, DC.

Denison, E. E. (1985). Trends in American economic growth, 1929–1982. Brookings Institution, Washington, DC.

Diewert, W. E., and Smith, A. M. (1994). Productivity measurement for a distribution firm. National Bureau of Economic Research Working Paper No. 4812 (July).

Dos Santos, B. L., Peffers, K. G., and Mauer, D. C. (1993). The impact of information technology investment announcements on the market value of the firm. *Information Systems Research* **4**(1), 1–23.

Dos Santos, B. L., Peffers, K. G., and Mauer, D. C. (1991). The value of investments in information technology: An event study. Kannert Graduate School of Management, Purdue University.

Dudley, L., and Lasserre, P. (1989). Information as a substitute for inventories. *European Economic Review* **31,** 1–21.

Dulberger, E. R. (1989). The application of hedonic model to a quality adjusted price index for computer processors. *In Technology and Capital Formation* (Jorgenson and Landau, Eds.), MIT Press, Cambridge, MA.

Fisher, F. M., and Griliches, Z. (1995). Aggregate price indices, new goods, and generics. *Quarterly Economics* **CX**(1), 229–244.

Franke, R. H. (1987). Technological revolution and productivity decline: Computer introduction in the financial industry. *Technological Forecasting and Social Change* **31,** 143–154.

Gordon, R. J. (1990). *The Measurement of Durable Goods Prices.* University of Chicago Press, Chicago (see especially Chapter 6, Electronic Computers).

Gordon, R. J. (1987a). Productivity, wages, and prices inside and outside of manufacturing in the U.S., Japan, and Europe. *European Economic Review* **31**(3), 685–739.

Gordon, R. J. (1987b). The postwar evolution of computer prices. National Bureau of Economic Research Working Paper No. 2227.

Gordon, R. J., and Baily, M. N. (1989). Measurement issues and the productivity slowdown in five major industrial countries. International Seminar on Science, Technology and Economic Growth, Paris, France.

Gremillion, L. L., and Pyburn, P. J. (1985). Justifying decision support and office automation systems. *Journal of Management Information Systems* **2**(1).

Griliches, Z. (1995). Comments on measurement issues in relating IT expenditures to productivity growth. *Economics of Innovation and New Technology* **3,** 317–321.

Griliches, Z. (1994). Productivity, R&D, and data constraints. *American Economic Review* **84**(1).

Griliches, Z. (1992). The search for R&D spillovers. *Scandinavian Economics* **94,** Supplement, pp. 29–47.

Griliches, Z., and Cockburn, I. (1994). Generics and new goods in pharmaceutical price indexes. *American Economic Review* **LXXXIV.**

Griliches, Z. (Ed.) with the assistance of Ernst R. Berndt, Timothy F. Bresnahan, and Marilyn E. Manser. (1992). *Output Measurement in the Service Sectors.* NBER Studies in Income and Wealth, Vol. 56, University of Chicago Press.

Grove, A. S. (1990). The future of the computer industry. *California Management Review* **33**(1), 148–160.

Gurbaxani, V., and Mendelson, H. (1989). The use of secondary data in MIS research. University of California, Irvine.

Hammer, M. (1990). Reengineering work: Don't automate, obliterate. *Harvard Business Review,* July–August, pp. 104–112.

Hammer, M., and Champy, J. (1993). *Reengineering the Corporation,* HarperBusiness, New York.

Harris, S. E., and Katz, J. L. (1991). Organizational performance and information technology investment intensity in the insurance industry. *Organizational Science* **2**(3), 263–296.

Hausman, J. A. (1994). Valuation of new goods under perfect and imperfect competition. National Bureau of Economic Research Working Paper No. 4970 (December).

Hitt, L., and Brynjolfsson, E. (1994). Three faces of IT value: The theory and evidence. Proc. Fifteenth International Conference on Information Systems, December.

Jonscher, C. (1994). An economic study of the information technology revolution. *In Information Technology and the Corporation of the 1990s: Research Studies* (Thomas J. Allen and Michael S. Scott Morton, Eds.), Oxford University Press, pp. 5–42.

Jonscher, C. (1983). Information resources and economic productivity. *Information Economics and Policy* **1,** 13–35.

Jorgenson, D. W., and Landau, R. (Eds.) (1989). *Technology and Capital Formation,* MIT Press, Cambridge, MA.

Jorgenson, D. W., and Stiroh, K. (1995). Computers and growth. *Economics of Innovation and New Technology* **3,** 295–316.

Kaplan, R. (1989). Management accounting for advanced technological environments. *Science* **245,** 819–823.

Kaplan, R., and Norton, D. P. (1992). The balanced scorecard—Measures that drive performance. *Harvard Business Review,* January–February, pp. 71–79.

Katz, L. F., and Krueger, A. B. (1994). How computers have changed the workplace, 1984–1993. Unpublished paper, Harvard University.

Kemerer, C. F., and Sosa, G. L. (1991). Systems development risks in strategic information systems. *Information and Software Technology* **33**(3), 212–223.

Kriebel, C. H. (1989). Understanding the strategic investment in IT. *In Information Technology and Management Strategy* (K. Lauden and J. A. Turner, Eds.), Prentice Hall, Englewood Cliffs, NJ.

Krueger, A. B. (1993). How computers have changed the wage structure: Evidence from micro-data, 1984–1989. *Quarterly Journal of Economics* **108**(1), 33–60.

Kwon, M. J., and Stoneman, P. (1995). The impact of technology adoption on firm productivity. *Economics of Innovation and New Technology* **3,** 219–233.

Landauer, T. K. (1995). *The Trouble with Computers,* The MIT Press, Cambridge, MA.

Lasserre, P. (1988). Project on the impact of information on productivity. Unpublished Paper, MIT.

Lau, L. J., and Tokutsu, I. (1992). The impact of computer technology on the aggregate productivity of the United States: An indirect approach. Unpublished Paper, Stanford University.

Lichtenberg, F. R. (1995). The output contributions of computer equipment and personnel: A firm-level analysis. *Economics of Innovation and New Technology* **3,** 201–217.

Loveman, G. W. (1994). An assessment of the productivity impact of information technologies. *In Information Technology and the Corporation of the 1990s: Research Studies,* (Thomas J. Allen and Michael S. Scott Morton, Eds.), Oxford University Press, pp. 84–110.

Malone, T., and Rockart, J. (1991). Computers, networks and the corporation. *Scientific American* **265**(3), 128–136.

Mark, J. A. (1982). Measuring productivity in the service sector. *Monthly Labor Review,* June.

McKersie, R. B., and Walton, R. E. (1991). Organizational change. In *The Corporation of the 1990s* (M. S. Scott Morton, Ed.), Oxford University Press, pp. 244–277.

Morrison, C. J., and Berndt, E. R. (1991). Assessing the productivity of information technology equipment in U.S. manufacturing industries. National Bureau of Economic Research Working Paper No. 3582 (January).

Nelson, R. R. (1981). Research on productivity growth and productivity differences: Dead ends and new departures. *Journal of Economic Literature* **29,** 1029–1064.

Noyelle, T. (1990). *Skills, Wages, and Productivity in the Service Sector.* Westview Press, Boulder, CO.

Oliner, S. D., and Sichel, D. E. (1994). Computers and output growth revisited: How big is the puzzle? *Brookings Papers on Economic Activity* (2), 273–334.

Osterman, P. (1986). The impact of computers on the employment of clerks and managers. *Industrial and Labor Relations Review* **39,** 175–186.

Parsons, D. J., Gotlieb, C. C., and Denny, M. (1990). Productivity and computers in Canadian banking. University of Toronto Department of Economics Working Paper No. 9012 (June).

Porat, M. (1977). *The Information Economy: Definition and Measurement.* U.S. Government Printing Office, Washington, DC.

Porter, M. E., and Miller, V. E. (1985). How information gives you competitive advantage. *Harvard Business Review,* July–August, pp. 149–160.

Pulley, L. B., and Braunstein, Y. M. (1984). Scope and scale augmenting technological change: An application in the information sector. Juswalla and Ebedfield.

Roach, S. S. (1991). Services under siege: The restructuring imperative. *Harvard Business Review* **39**(2), 82–92.

Roach, S. S. (1989a). Pitfalls of the new assembly line: Can service learn from manufacturing? Morgan Stanley Special Economic Study, New York (June 22).

Roach, S. S. (1989b). America's white-collar productivity dilemma. *Manufacturing Engineering,* August, pp. 104.

Roach, S. S. (1987). America's technology dilemma: A profile of the information economy. Morgan Stanley Special Economic Study (April).

Romer, P. M. (1987). Crazy explanations for the productivity slowdown. *In NBER Macroeconomics Annual: 1987* (Stanley Fisher, Ed.), MIT Press, Cambridge, MA.

Romer, P. M. (1986). Increasing returns and long-run growth. *Journal of Political Economy* **94**(5), 1002–1037.

Scherer, F. (1980). *Industrial Market Structure and Economic Performance,* Rand-McNally, Chicago.
Schneider, K. (1987). Services hurt by technology: Productivity is declining. *The New York Times,* June 29, pp. D1, D6.
Scott Morton, M. S. (Ed.) (1991). *The Corporation of the 1990s: Information Technology and Organizational Transformation.* Oxford University Press.
Siegel, D. (1994). The impact of computers on manufacturing productivity growth: A multiple-indicators, multiple-causes approach. SUNY at Stony Brook Working Paper (May).
Siegel, D., and Griliches, Z. (1992). Purchased services, outsourcing, computers, and productivity in manufacturing. *In Output Measurement in the Service Sectors* (Z. Griliches *et al.,* Eds.), University of Chicago Press, Chicago.
Snow, C. P. (1966). Government science and public policy. *Science* **151,** 650–653.
Stabell, C. B. (1982). Office productivity: A microeconomic framework for empirical research. *Office: Technology and People* **1,** 91–106.
Strassmann, P. A. (1990). *The Business Value of Computers: An Executive's Guide.* Information Economics Press, New Canaan, CT.
Strassmann, P. A. (1985). *Information Payoff: The Transformation of Work in the Electronic Age.* Free Press, New York.
Thurow, L. (1987). Economic paradigms and slow American productivity growth. *Eastern Economic Journal* **13,** 333–343.
Trajtenberg, M. (1990). Product innovations, price indices and the (mis)measurement of economic performance. National Bureau of Economic Research Working Paper No. 3261 (February).
Watts, L. (1986). What price automation? *Northeastern University Alumni Magazine,* pp. 21–24.
Weill, P. (1992). The relationship between investment in information technology and firm performance: A study of the valve manufacturing sector. *Information Systems Research* **3**(4), 307–333.
Weitzendorf, T., and Wigand, R. (1991). Tasks and decisions: A suggested model to demonstrate benefits of information technology. Institute for Information Science Working Paper, Graz, Austria.
Wilson, D. D. (1995). IT investment and its productivity effects: An organizational sociologist's perspective on directions for future research. *Economics of Innovation and New Technology* **3,** 235–251.
Zachary, G. P. (1991). Computer data overload limits productivity gains. *Wall Street Journal,* November 11, p. B1.