Information Technology and Productivity:
A Review of the Literature

Erik Brynjolfsson
Shinkyu Yang

MIT Sloan School of Management
Cambridge, Massachusetts

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Abstract

During the 1980s, the relationship between information technology (IT) and productivity became a source of debate: the astonishing improvements in computers' underlying capabilities proved almost impossible to assess in terms of their effect on productivity. Fueled in part by the emergence of empirical research on IT productivity that generally did not identify significant productivity improvements, the perception that IT failed to live up to its promise prevailed. Recent research is more encouraging, as new data are identified and more sophisticated methodologies are applied. Several researchers document IT's positive effect on productivity performance. Additionally, others approach IT's contribution from different perspectives, examining its effect on intermediate measures, on consumer surplus, and on economic growth. Consequently, our presumption of a "productivity paradox" has diminished considerably. However, a careful review indicates that unequivocal evidence still remains elusive, with new questions emerging even as old puzzles fade. This survey categorizes relevant studies into four groups, identifies remaining productivity puzzles, and reviews four possible explanations for them: mismeasurement, lags, redistribution and mismanagement. The paper concludes with recommendations for investigating each of these explanations, including more careful applications of traditional methodologies, as well as employment of alternative, broader metrics of welfare to assess and enhance the benefits of IT.

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

Over the past decade, both academics and the business press have periodically revisited the so-called "productivity paradox" of computers. On one hand, delivered computing-power in the US economy has increased by more than two orders of magnitude in the past two decades (figure 1). On the other hand, productivity, especially in the service sector, seems to have stagnated (figure 2). Despite the enormous promise of information technology (IT) to effect "the biggest technological revolution men have known" [Snow, 1966], disillusionment and even frustration with the technology are evident in statements like "No, computers do not boost productivity, at least not most of the time" [Economist, 1990] and headlines like "Computer Data Overload Limits Productivity Gains" [Zachary, 1991].

Interest in the "productivity paradox", as it has become known, has engendered a significant amount of research. Although researchers analyzed statistics extensively, they found little evidence that information technology significantly increased productivity in the 1970s and 1980s. The results were aptly characterized by Robert Solow's quip that "you can see the computer age everywhere but in the productivity statistics,"[1] and Bakos and Kemerer's [1992] summation that, "These studies have fueled a controversial debate, primarily because they have failed to document substantial productivity improvements attributable to information technology investments."

Now, after researchers such as Brynjolfsson and Hitt [1993, 1995], and Lichtenberg [1995] found firm-level evidence that IT investments earned substantial returns, the media pendulum has swung in the opposite direction. *Businessweek*'s proclamation of "the productivity surge" due

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

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. As more research is conducted, we are gradually developing a clearer picture of the relationship between IT and productivity. However, productivity measurement isn't an exact science. Our tools are still blunt, and our conclusions not as definitive as we would like. While one study shows a negative correlation between total factor productivity and high share of high-tech capital formation during 1968-1986 period [Berndt and Morrison, 1995], another study suggests that computer capital contributes to growth more than ordinary capital during the similar period [Jorgenson and Stiroh, 1995]. Hitt and Brynjolfsson [1994] report positive effects of IT based on output and consumer surplus measures. On the other hand, Landauer [1995] de-emphasizes the findings of recent studies and documents various cases of "the trouble with computers". At this stage, the academic research results are inconsistent on a number of dimensions, including measures of performance, methodologies, and data sources.

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 the "productivity payoff" often overstate reality and overlook the limitations of the academic studies on which they were based. Although progress in this area of research has been quite substantial, a consensus about the relationship between IT investment and economic performance eludes us. 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

[2] 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.

how information technology affects productivity either at the level of the firm or for the economy as a whole is extremely limited" [Wilson, 1995].

This paper seeks to contribute to the research effort by summarizing what we know and don't know, by distinguishing the central issues from peripheral ones, and by clarifying the questions to be profitably explored in future research. 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 the same level of aggregation, results may depend on different measures of performance or research methods. While this review emphasizes economic approaches to both theory and empirics, it is hoped that the process of reviewing studies of the productivity controversy will serve as a useful springboard for examining other 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. Among the most common is the BEA's (U.S. Bureau of Economics Analysis) category "Office, Computing and Accounting Machinery (OCAM) which consists primarily of computers. Some researchers looks specifically at computer capital, while others consider the BEA's broader category, "Information Processing Equipment (IPE)." IPE includes communications equipment, scientific and engineering instruments, photocopiers and related equipment. Besides, 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 at work.

• "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 an increase in capital intensity. However, lack of data often renders this consideration moot.

• 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", often using "hedonic" methods, to eliminate the effects of inflation without ignoring quality changes.

Trends:

• The price of computing has dropped by half every 2-3 years (figure 3a and figure 3b).[4] If progress in the rest of the economy had matched progress in the computer sector, a Cadillac would cost $5.91, while ten 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 over 10% of new investment in capital equipment by American firms (figure 4, table 2).[6]

• Information processing continues to be the principal task undertaken by America's work force. Over half the labor force is employed in information-handling activities (figure 5).

• Overall productivity has 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 (figure 2, table 4). However, there is some evidence of a rebound more recently.

• White collar productivity statistics have been essentially stagnant for 20 years (figure 6).

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[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 well 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, 1987].

[5] This comparison was inspired by the slightly exaggerated claim in Forbes [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 $5.91 Cadillac is based on a price of $36,635 for a 1996 *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 actual 1996 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.

These trends suggest the two central questions which comprise the productivity paradox: 1) Why would companies invest so heavily in information technology if it didn't add to productivity? 2) If information technology *is* contributing to productivity, why is it so difficult to measure it?

In seeking to answer these questions, this paper builds on a number of previous literature surveys. Much of the material in section II and III is adapted from a previous paper by Brynjolfsson [1993]. An earlier study by Crowston and Treacy [1986], identified 11 articles on the "impact of IT on enterprise level performance" by searching ten journals from 1975 to 1985. They conclude that attempts to measure the impact of IT were surprisingly unsuccessful, and attribute this to the lack of clearly defined variables, which in turn stems from inadequate reference disciplines and methodologies.

A review of research combining information systems and economics, by Bakos and Kemerer [1992], includes particularly relevant work in sections on "macroeconomic impacts of information technology" and "information technology and organizational performance". Many of the papers that seek to directly assess IT productivity begin with a literature survey. The reviews by Brooke [1992]; Barua, Mukhopadhyay and Kriebel [1991]; and Berndt and Morrison [1995] were particularly useful. Most recently, the first part of Landauer's [1995] book details research results surrounding the productivity puzzle. Wilson [1995] also provides a useful survey of twenty articles.

Although this review considers about 150 articles, it cannot claim to be comprehensive. Rather, it aims to clarify for the reader the principal issues surrounding IT and productivity, by assimilating the results of a computerized literature search of 30 of the leading journals in both information systems and economics,[7] and by including discussions with many of the leading researchers in this area, who helped identify recent research that has not yet been published.

The remainder of the paper is organized as follows. The next section summarizes the empirical research that has attempted to measure the productivity of information technology. Section III considers aspects of the productivity puzzle which remain unsolved in spite of recent studies confirming IT's favorable impact on productivity. It classifies the explanations for the remaining paradox into four basic categories and assesses the components of each. Section IV concludes with summaries of the key issues identified and with some suggestions for further research.

II. Research on the Productivity Effects of Information Technology

Productivity is the fundamental measure of a technology's contribution. While major success stories exist, so do equally impressive failures. (See, for example [Kemerer and Sosa, 1991; Schneider, 1987].) The lack of accurate quantitative measures for the output and value created by information technology has made the MIS manager's job of evaluating investments particularly difficult. Academics have had similar problems assessing the contributions of this critical new technology, and sometimes this has been interpreted as a negative signal of its value.

In the 1980s and early 1990s, disappointment in information technology was chronicled in articles disclosing broad negative correlations with economy-wide productivity and information worker productivity. Several econometric estimates also indicated low IT capital productivity in a variety of manufacturing and service industries. More recently, researchers began to find

[7] The journals searched included *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

positive relationships between IT investment and various measures of economic performance. The principal empirical research studies of IT and productivity are listed in table 1.

Table 1: Principal Empirical Studies of IT and Productivity

	Cross-sector	**Manufacturing**	**Services**
Aggregate Level Studies (Economy-wide and Industry-level)	Jonscher [1983], Jonscher [1994]	Morrison & Berndt [1991]	Brand & Duke[1982]
	Baily [1986b], Baily & Chakrabarti [1988], Baily & Gordon [1988]	Berndt et al. [1992] Berndt & Morrison [1995]	Baily [1986a]
	Roach [1987], Roach [1988], Roach [1989b]	Siegel & Griliches [1992]	Roach [1987], Roach [1989a], Roach [1991]
	Brooke [1992]	Siegel [1994]	
	Lau & Tokutsu [1992]		
	Oliner & Sichel [1994]		
	Jorgenson & Stiroh [1995]		
	Brynjolfsson [1995]		
Micro-Level Studies (Firms and Workers)	Osterman [1986]	Loveman [1994]	Cron & Sobol [1983]
	Dos Santos [1993]	Weill [1988, 1992]	Pulley & Braunstein [1984]
	Krueger [1993]	Dudley & Lasserre [1989]	Bender [1986]
	Brynjolfsson & Hitt [1994]	Barua, Kriebel & Mukhopadhyay [1991]	Bresnahan [1986]
	Hitt & Brynjolfsson [1994]	Brynjolfsson & Hitt [1993] Brynjolfsson & Hitt [1995]	Franke [1987]
	Lichtenberg [1995]		Strassmann [1985] Strassmann [1990]
			Harris & Katz [1991]
			Parsons et al. [1990]
			Diewert & Smith [1994]

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.

A. Economy-wide Productivity and Information Worker Productivity

1. The Issue

One of the core puzzles in economics is the productivity slowdown that began in the early 1970s. Labor productivity growth dropped from about 2.5% per year for 1953-1968 to about 0.7% per year for 1973-1979. Multi-factor productivity growth, which takes into account changes in capital, declined from 1.75% a year to 0.32% [Baily, 1986b]. Even after accounting for factors such as the oil price shocks, changes in labor quality and potential measurement errors, most researchers still find an unexplained residual drop in productivity compared to the first half of the post-war period. The sharp drop in productivity roughly coincided with the rapid increase in the use of information technology (figure 1).

Jorgenson and Stiroh's [1995] more recent growth accounting confirms this trend. Their calculation shows that average multifactor productivity growth dropped from 1.7% per year for 1947-73 period to about 0.5% for the 1973-1992 period. At the same time, OCAM capital as a percentage of all producers' durable equipment (PDE) investment rose from about half percentage point in the sixties to 12% in 1993. The broader category of IT capital, information processing equipment (IPE), now constitutes 34.2% of all PDE investment (table 2). Although productivity growth, especially in manufacturing, has rebounded somewhat recently, the overall negative correlation between economy-wide productivity and the advent of computers drives many arguments proposing that information technology has not helped U.S. productivity or even that information technology investments have been counter-productive [Baily, 1986b].

This link was made more explicit by Stephen Roach's [1987, 1988] research focusing specifically on information workers, regardless of industry. In the past, office work was not very capital intensive, but recently the level of information technology capital per ("white collar") information worker has begun approaching 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 cites statistics indicating that output per production worker grew by 16.9% between the 1970s and 1986, while output per information worker decreased by 6.6%. He concluded: "We have in essence isolated America's productivity shortfall and shown it to be 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.[8]

Table 2. Selected Investment Components in 1970 and 1993

($billion, current dollars)

	Invest.	**Percentage of**		**Invest**	**Percentage of**	
Item	**1970**	**Fixed I.**	**PDE**	**1993**	**Fixed I.**	**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.

2. Size of the Puzzle

Because researchers and managers expect and sometimes experience revolutionary benefits from IT investment, juxtaposing heavy IT investment growth and the productivity slowdown makes for dramatic news. Upon closer examination, however, the alarming correlation between IT investment and lower productivity at the level of the entire US economy is not compelling

[8] 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.

because so many other factors affect productivity and, until recently, computers were not a major share of the economy.

Consider the following order of magnitude estimates. In 1992, IT capital stock (OCAM) was equal to about 10% of GNP, when the base year is 1987. If, hypothetically, IT were being used efficiently and its marginal product were 50% (exceeding the return to most other capital investments), then the level of GNP would be directly increased about 5% (10% x 50%) because of the existence of our current stock of IT. However, information technology capital stock did not jump to its current level in the past year alone. Instead, the increase must be spread over about 30 years, suggesting an average annual contribution to aggregate GNP growth of 0.15%. This would be very difficult to isolate because so many other factors affected GNP, especially in the relatively turbulent 1970s and early 1980s. Indeed, if the marginal product of IT capital were anywhere from 0% to +65%, it would still not have affected aggregate GNP growth by more than about 0.2% per year.[9] Comprehensive growth accounting exercises (See section II.D.) confirm the above back-of-envelope estimation.

This is not to say that computers have not had significant effects in specific areas, like transaction processing, or on other characteristics of the economy, like employment shares, organizational structure or product variety. Rather it suggests that very large changes in capital stock are needed to measurably change total output. Yet, as the growth in information technology stock remains strong and the share of the total economy accounted for by computers is becoming quite substantial, we should begin to notice changes at the level of aggregate GNP.

In fact, for recent years the growth contribution of computer capital is larger as a result of accelerated IT capital accumulation. Moreover, some recent studies report excess return on IT

[9] In dollar terms, 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 as compared with pre-computer levels of output. Compare to the $100,000 or so in salary and overhead that it costs to employ this worker and the expectations for a technological "silver bullet" seem rather ambitious.

capital. Using various assumptions of excess returns on computer investment, Oliner and Sichel [1994] show that the contribution may go up to 0.38% per year for 1984-1991 period. Jorgenson and Stiroh [1995] report a slightly higher contribution; their numbers for 1979-1992 period are 0.38% - 0.52% per year. In fact, this productivity improvement may be involved in the recent "jobless recovery" of the US economy.[10] While abundant anecdotal evidence in the business press hints at IT-related productivity improvement, more careful studies are needed to see the whole picture.

3. Information Workers with Computers

As for the apparent stagnation in white collar productivity, one should bear in mind that relative productivity cannot be directly inferred from the number of information workers per unit output. For instance, if a new delivery schedule optimizer allows a firm to substitute a clerk for two truckers, the increase in the number of white collar workers is evidence of an increase, not a decrease, in their relative productivity and in the firm's productivity as well. Osterman [1986] suggests that this is why clerical employment often increases after the introduction of computers; and Berndt et al. [1992] confirm that information technology capital is, on average, a complement for white collar labor even as it leads to fewer blue collar workers. Berman, Bound and Griliches [1994] also find that "increased use of non production workers is strongly correlated with investment in computers and in R&D." Unfortunately, more direct measures of office worker productivity are exceedingly difficult. Because of the lack of hard evidence, Panko [1991] has gone so far as to call the idea of stagnant office worker productivity a myth, although he cites no evidence to the contrary.

Independent of its implications for productivity, growth in the white collar work force cannot be blamed on information technology. Although almost half of workers now use computers in their jobs [Katz and Krueger, 1994], the ranks of information workers began to surge even before

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[10] We should note Oliner and Sichel's opinion about the recent productivity recovery. They assert that the recent recovery is cyclical rather than computer-related, referring to Gordon [1993].

the advent of computers [Porat, 1977]. Jonscher [1994] goes so far as to argue that causality goes the other way: the increased demand for information enabled economies of scale and learning in the computer industry, thereby reducing costs.

In line with this argument, the unbalanced growth hypothesis may provide a sensible economic explanation.[11] Economic growth may slow down because of intrinsically slow technical progress in the white collar 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. This hypothesis may partially answer our first research question: why are companies investing so heavily in IT if it doesn't add to productivity? They are forced to, at least in the developed countries. As income level increases, people demand more services of white collar sectors. Since white collar sectors are also prone to output mismeasurement, the story becomes more complicated. In short, IT may not be a source of the productivity slowdown, but simply a response to the overall transformation of the economy. In this view, IT is not the culprit behind the productivity slowdown, but a byproduct.

An important study of computer-using workers by Krueger [1993] indirectly supports this view. He found computer-using workers earned 10% - 18% higher wages than non-users. In 1984, 24.6% of workers were using computers at work. By 1989, this number had grown to 37.4 %.[12] Assuming that workers are paid according to their productivity, this implies that computers at work increase the level of GDP by 3%.[13] Although this number is not substantial enough to compensate the annual 1% productivity slowdown after the early 1970s, it indicates that information technology may actually boost office worker productivity, which has decreased as a result of other factors.

[11] See, for example, Baumol [1967], and Baumol, Blackman, and Wolff [1985].

[12] Katz and Krueger [1994] report that this share of workers had risen to 47% by 1993.

[13] 3% = 0.7 x 0.1 x 37.4%, 0.1 is the excess marginal product, and 0.7 is the labor share of GDP.

B. Industry-Level Studies of Information Technology Productivity

The last 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 from aggregation, but it is often difficult to find data representative for the whole economy. Industry-level studies may provide middle-of-the-road alternative. Table 3 summarizes some of the important studies. While earlier studies failed to identify positive effects of IT, recent studies found more encouraging results. 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 was comparable, but since then the trends have diverged significantly.[14] 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 4), this has been taken as indirect evidence of poor information technology productivity.

Roach's widely cited research on white collar productivity, discussed above, focused principally on IT's performance in the service sector [1987a, 1989a, 1989b, 1991]. Roach argues that IT is an effective substitute for labor in most manufacturing industries, but has paradoxically been associated with bloating white-collar employment in services, especially finance. He attributes this to relatively keener competitive pressures in manufacturing and foresees a period of belt-tightening and restructuring in services as they also become subject to international competition.

[14] According to government statistics, from 1953 to 1968, labor productivity growth in services averaged 2.56%, vs. 2.61% in manufacturing. For 1973 to 1979, the figures are 0.68% vs. 1.53%, respectively [Baily, 1986]. However, Gordon and Baily [1989] and Griliches [1994, 1995] suggest that measurement errors in US 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 non-electrical machinery category (containing the computer producing industry) has shown tremendous growth. As a result, overall manufacturing productivity growth has rebounded from about 1.5% in the 1970s to 3.5% in the 1980s. See section III.A of this paper.

However, studies of manufacturing also found evidence of a productivity paradox. Berndt and Morrison have written two papers using a broader data set from the US Bureau of Economic Analysis (BEA) that encompasses the whole U.S. manufacturing sector. The first [Morrison and Berndt, 1991], which examined a series of highly parameterized models of production, 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 second paper [Berndt and Morrison, 1995] took a less structured approach and examined broad correlations of IT with labor productivity and multifactor productivity, as well as other variables. 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 IT was correlated with significantly 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. Among their findings was 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 they raised regarding the reliability of the data and government measurement techniques. Their findings seem contradictory to those of Berndt and Morrison [1995]. However, Berndt and Morrison [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 is mainly used for industry-level analysis, but it is subject to subtle biases due to the unintuitive 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's [1994] recent paper is an attempt to tackle some aspects of data problems. He deals with 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 delicate. He observes that computers may exacerbate errors in the measurement of productivity: firms invest in computers not only for cost reduction but also for quality improvement.[15] As the latter is not fully taken into account in the traditional statistics, the errors in output measurement are correlated with computer investment. These two kinds of errors cause both bias and inefficiency in estimation. After controlling these errors using a "multiple-indicators and multiple-causes" model, he found a positive and significant relationship between multifactor productivity growth and computer investment. Among his findings, computer investment is positively correlated with both product quality and labor quality. These latter results are consistent with Brynjolfsson [1994], Berndt and Morrison [1995], and Berman, Bound and Griliches [1994].

Table 3: Industry-Level Studies

Study	**Sector**	**Data source**	**Findings**
Brand [1982]	Services	BLS	Productivity growth of 1.3%/yr in banking
Roach [1987], Roach [1989a], Roach [1991]	Services	Principally BLS, BEA	Vast increase in IT capital per information worker while measured output decreased
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 majority of industries; correlated with more labor
Siegel & Griliches [1992]	Manufacturing	Multiple gov't sources	IT using industries tend to be more productive; government data is unreliable
Siegel [1994]	Manufacturing	Multiple gov't sources	A multiple-indicators and multiple-causes model captures significant MFP effects of computers

15 See, for example, Brynjolfsson [1994]. A survey of IT managers found that the primary reason that firms invest in computers is to improve customer service. Cost reduction, timeliness, quality, and flexibility follow the customer service.

Table 4. Investment in Computers (OCAM) in the U.S. economy.

(current dollars, percentage of total)

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*	0.1	0.3	0.2
Non-service 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*	19.9	16.3	20.0
Finance*	32.5	38.7	37.8
Other Services*	11.6	17.0	13.9
Services Total	**68.0**	**78.2**	**78.6**
Unmeasurable Sectors*	**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]

* Unmeasurable sectors: construction, trade, finance and other services; in these sectors outputs are difficult to measure, relative to measurable sectors.

C. Firm-Level Studies of Information Technology Productivity

Over the last ten years, there are many firm-level studies examining the relationship between IT investment and firm performance. We observe an interesting trend in the results of these studies; the use of larger and more recent datasets tends to generate evidence of IT's positive effect on firm performance. In addition, research results in manufacturing often shows stronger effects than studies of services, probably because of better measurement.

1. Service Sector Studies

Strassmann [1985] reports disappointing evidence in several 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, while others do not. In his later book [1990], he concludes that "there is no relation between spending for computers, profits and productivity".

There have been several studies of IT's impact on the performance of various types of financial services firms. A study by Parsons, Gottlieb and Denny [1990] estimated a production function for banking services in Canada and found that overall, the impact of IT on multifactor productivity was quite low between 1974 and 1987. They speculate that IT has positioned the industry for greater growth in the future. Similar conclusions are reached by Franke [1987], who 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. On the other hand, Brand and Duke [1982], using BLS data and techniques, found that moderate productivity growth had already occurred in banking.

Harris and Katz [1991] and Bender [1986] looked at data on the insurance industry from the Life Office Management Association Information Processing Database. They found a positive relationship between IT expense ratios and various performance ratios although at times the relationship was quite weak. Alpar and Kim's [1991] study of 759 banks indicates cost-reducing effects of IT. A 10% increase in IT capital is associated with 1.9% decreases in total costs. Several case studies of IT's impact on performance have also been done, including one by Weitzendorf and Wigand [1991] which developed a model of information use in two service corporations, and a study of an information services firm by Pulley and Braunstein [1984], which found an association with increased economies of scope.

Using a production function approach, Brynjolfsson and Hitt [1993] found that for the service firms in their sample, gross marginal product averaged over 60 percent per year. Their recent study reports another important result: the contribution of IT to output is as high 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 due to mismeasurement of output in aggregate datasets.

Diewert and Smith [1994] provide an interesting case study of a large Canadian retail firm. According to their accounting frame-work, the distribution firm experienced an astounding 9.4% quarterly multi-factor 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 subject to statistical aggregation. Unfortunately, even when abundant data exist, classifications sometimes seem arbitrary. For instance, in accordance with a fairly standard approach, Parsons, Gottlieb and Denny [1990] treated *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 also becomes particularly apparent in some of the service sector studies. In particular, researchers and consultants have increasingly emphasized the theme of re-engineering work when introducing major IT investments.[16] As Wilson [1995] suggests, whether or not the reengineering efforts are the main explanation for Brynjolfsson and Hitt's [1993, 1995] findings poses an interesting question. A recent survey found tantalizing evidence that firms which had reengineered recently had significantly higher productivity than their competitors [Brynjolfsson, 1994].

Table 5: Firm-Level Studies: Services

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] Strassmann [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 [19 91]	LOMA insurance data for 40	Weak positive relationship between IT and various performance ratios
Noyelle [1990]	US and French industry	Severe measurement problems in services
Parsons et al. [1990]	Internal operating data from 2 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 2 companies	Interactive model of information use
Diewert & Smith [1994]	A large Canadian retail firm	Multi-factor productivity grows 9.4% per quarter over 6 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

2. Manufacturing 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 table 6. A study by Gary Loveman [1994] provided some of the first econometric evidence of a potential problem when he examined data from 60 business units (namely, the MPIT subset of the PIMS data set). As is common in productivity literature, he used 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 output was approximately zero over the five year period studied in almost every subsample he examined. His findings were fairly robust to a number of variations on his basic formulation.

[16] See, for example, [Davenport, 1990, 1993; Hammer, 1990; Hammer & Champy, 1993; Champy, 1995]

While Loveman's dependent variable was final output, Barua, Kriebel and Mukhopadhyay [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 of performance, although the magnitude of the effect was generally too small to measurably affect final output. 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] was also able to disaggregate IT by use, and found that significant productivity could 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. email infrastructure).

In a series of studies utilizing large firm-level surveys by International Data Group (IDG), Brynjolfsson and Hitt report IT's favorable impact on productivity. Their first study [Brynjolfsson and Hitt, 1993] found that while gross marginal product of non-computer capital ranges from 4.14% to 6.86%, that of computer capital averages 56% - 68%. The results of this and their subsequent study [Hitt and Brynjolfsson, 1994] imply the rejection of the following three null hypotheses:

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's.

Their point estimates of gross marginal products are rather surprising, since at the margin computer capital generates 10 times more output than other capital of equal value. Their later study shows up to half of the excess returns imputed to IT could be attributed to firm specific effects [Brynjolfsson and Hitt, 1995]. Nonetheless, a back-of-envelope calculation shows that the implicit marginal product of computer capital in Jorgenson and Stiroh's study is also over 60%.[17]

One may doubt the large gross marginal product of information technology capital, wondering what friction or market failure prevents firms from investing in more computers until the marginal products of all capital goods become equal. [18] Part of this differential is due to the higher user cost of computer capital. According to Oliner and Sichel [1994], over 1970-92 the user cost of computer capital averages 36.6 % per year, while that of other types of capital is 15.4%.[19] 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. [20]

Lichtenberg [1995] confirms the results of Brynjolfsson and Hitt, using the same data source and similar methods. He also analyzes *Informationweek* survey data and uncovers essentially the same results. His formal tests reject the above null hypotheses. One important extension in Lichtenberg's study is that he also reports the marginal rate of substitution between IT and non-IT workers. Evaluated at the sample mean, it is 6: one IT worker can be substituted for six non-IT workers.

Table 6: Firm-Level Studies: Manufacturing and Cross Sector

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[17] 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 1985-1992. 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 1985-1987 period (24%). Now computers' nominal income share is equal to (computers capital's marginal product x computer capital / GDP). In 1987, computer capital stock amounts to $113.24 billion and GDP is $4.5399 trillion, thus the implicit marginal product of computers is estimated to 63% = (0.38%)* ($4539.9/$113.24)/(24%)

[18] See, for example, Oliner and Sichel [1994] and Robert J. Gordon's comment on the paper.

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

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

Study	Data source	Findings
Loveman [1994]	PIMS/MPIT	IT investments added nothing to output
Dudley & Lasserre [1989]		IT and communication reduces inventories
Weill [1992]	Valve manufacturers	Contextual variables affect IT performance Transaction processing IT produce positive results
Barua, Kriebel & Mukhopadhyay [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

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, calls for scrutiny. As Loveman is careful to point out, his results are based on dollar denominated outputs and inputs, and therefore depend on price indices which may not accurately account for changes in quality or the competitive structure of the industry. The results of both of these studies may also be unrepresentative to the extent that the relatively short 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, mitigates data problems to a substantial degree. Although one may still argue that the data set contains only large firms which may not be the representative random sample, it is the only comprehensive reliable source of IT spending. Indeed, Brynjolfsson and Hitt [1993] attribute the statistical significance of their findings not only to the more recent time period but also the large size of the IDG data set, which enables them to estimate returns for all factors with greater precision. Utilizing other large data sets, Kwon and Stoneman [1995] also show that use of computers and numerical control machines has positive impacts on output and productivity. Their data source is comprehensive surveys of the UK engineering industry undertaken in 1981, 1986, and 1993.

D. Contribution to Consumer Surplus and Economic Growth

While some researchers have focused on IT's effects on excess return or multifactor productivity, others have identified sizable contributions to consumer surplus and to economic growth. Some of important studies are summarized in table 8. Griliches [1992, 1994] emphasizes the distinction between "pecuniary externalities" and "non-pecuniary externalities or spill-overs." Pecuniary externalities are associated with the price decline of a factor input. When computer prices are declining exogenously, profit-maximizing firms are substituting computer systems for other input factors such as labor or space for inventories. Lowered prices of computers and other inputs shift marginal cost curves downward. Low marginal costs result in both more output and lower prices. The output increase is a measure of the pecuniary externality, since the benefits created by the computer sector are captured in terms of greater output of computer-using industries. Another measure of this pecuniary externality is consumer surplus. As computer prices fall, many firms and customers that could not afford computers become able to purchase them, while infra-marginal customers who were willing to pay higher prices enjoy a windfall of price reduction. When we consider that computers are mainly intermediate goods, the growth contribution measure and consumer surplus measure are closely related.

Pecuniary externalities directly increase labor productivity, yet they do not necessarily increase multifactor productivity. Pecuniary externalities by themselves do not change the production function. Instead they cause an input mix change, in this case substituting computers for other inputs, and output growth. Non-pecuniary externalities or spill-overs come from the more obscure source of technical change; we may expect that people have found smarter ways of making goods and services by exploiting information technology.[21] Not only does the input mix change, but also the production possibility frontier shifts out. In this case, both labor productivity and multifactor productivity should go up.

Bresnahan [1986] was the first to look at benefits from computer price decline. Assuming the benefits of price decline go to consumers and using the hedonic price index, he calculates that the consumer surplus was five or more times of computer expenditures in the late 1960s financial sector. Brynjolfsson [1995] estimates economy-wide consumer surplus, using assumptions similar to Bresnahan's. According to this research, 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. A comprehensive growth accounting is done by Jorgenson and Stiroh [1995]. One of their study's main contributions is the careful calculation of capital's service flow. Since Jorgenson and Stiroh assume that, unlike other physical capital, computers maintain their full ability until retirement, their estimation of computer capital's contribution becomes larger than that of Oliner and Sichel [1994]. Table 7 shows the results of Jorgenson and Stiroh's [1995] growth accounting. In the 1979-85 period computers and peripherals contribute to output growth by 0.52% per year. In the 1985-92 period, the contribution is 0.38% per year.[22]

The interesting feature of Oliner and Sichel's [1994] study is that they carefully examine the growth accounting implications of the various excess return hypotheses of computer capital. Their baseline estimate is that the contribution of computer capital to output growth is 0.16% per year for the 1970-1992 period. Using Romer's [1986, 1987] assumption of positive

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[21] 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, not too high.

externality of physical capital, the contribution goes up to 0.32%. When they use Brynjolfsson and Hitt's [1993] higher estimate for the return on computer capital, the contribution becomes 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 marginal product differential between computer-using workers and non-using workers, the contribution number goes up to 0.38%. Although the main theme of the paper is that per-year contribution up to 0.38% is not large enough to compensate the approximately 1% drop in output growth since the seventies, according to Jorgenson, "this is a pretty hefty contribution."[23]

Table 7. Growth Rates of Aggregate Output and Contribution of Factors (1947-92)

Variable	**Value Added**			**Contribution of Factors**				
		NonComp Share	Computer Share	Capital	NonComp Share	Computer Share	Labor	MFP
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)

The following rough calculation may provide some intuition about the size of the computer's contribution to national output. From Jorgenson and Stiroh [1995], take the simple average 0.45% contribution for 1979-1992 period (mean of 0.52% and 0.38%), and compare it with

22 The contribution dropped because the growth rate of real computer capital is lower for the 1979-1985 period than for the 1985-1992 period; nominal investment of computers did not increase much during the 1985-1992 period

0.72% (simple average, again) contribution of other capital. Because the share of computers in total capital stock was just 1.6% in 1993, these numbers imply that one unit of computer capital's contribution to output growth is equivalent to that of 98 units of other forms of capital.[24] This does not mean, however, that computer capital is almost 100 times more productive than other forms of capital; the number represents not the contribution to level of output but the contribution to growth of output. In 1993, GDP grew by $173 billion.[25] The computers' contribution was $29 billion, while other capital's contribution was $46 billion. The unexplained residual's (MFP) contribution is $40 billion.

Using data from 367 large firms generating 1.8 trillion dollars in output per year for the period 1988 to 1992, Brynjolfsson and Hitt [1994] provide an interesting growth accounting result. For their sample of firms, IT capital contributes about 1% per annum to output growth. This growth contribution exceeds that of ordinary capital in absolute value. Their calculation of IT capital's large contribution to growth is not unique. Lau and Tokutsu [1992] document even bigger numbers. They attribute approximately half of the real output growth (1.5% growth per annum) during the past three decades to computer capital. They also document computer capital's deflation effects; 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."[26]

In summary, the weight of evidence from various studies indicates that information technology capital generates billions of dollars annually for the US economy, both in terms of output growth and consumer surplus. Meanwhile, the recent firm-level analyses of Brynjolfsson and

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23 In a letter to Erik Brynjolfsson, Feb. 7, 1995.

24 98 = (0.72x98.4)/(0.45x1.6).

25 Survey of Current Business, March 1994, table 1-1, nominal dollars.

26 This quote is adopted from [Griliches,1995].

Hitt[1993, 95] and Lichtenberg [1995] have begun to ameliorate the shortfall of evidence regarding the productivity contribution of IT.

Table 8: 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 Gov't sources	Computer capital contributes half of output growth
Brynjolfsson & Hitt [1994]	IDG: Compustat	Growth contribution of computers is 1% per year among 367 US large firms
Oliner & Sichel [1994]	principally BEA	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.

III. Remaining Paradox and Leading Explanations

While some dimensions of the "information technology productivity paradox" have been addressed in recent research, two major aspects of the paradox persist. The first question is a mundane and long-term problem: whether positive evidence recently reported by some researchers is enough to bridge the gap between expected promises and delivered results of information technology. According to Griliches [1994], "some scattered evidence for the positive contribution of computers" is "not particularly strong, given the needle-in-the-haystack aspect of this problem."

The second question is more specific and calls for rather immediate inquiry. This issue concerns measures other than productivity. Hitt and Brynjolfsson [1994] looked for associations between IT spending and various business performance measures. Although they document IT's positive impact on output and consumer surplus, they do not find a significant positive correlation between IT spending and performance measures other than output. Neither Ahituv and Giladi [1993] nor Strassmann [1990] find evidence of IT's positive effects on profitability.

In summary, IT's contribution to output and productivity is documented in several important studies, but whether or not this output growth is beneficial to profits and market value is not yet clear.[27] In addition, some practitioners and researchers still believe that "the full power of the computer in increasing national productivity has not yet unfolded."[28] In this sense, the productivity paradox still awaits explanation. We now examine four basic approaches to answering these questions:

1) **Mismeasurement** of outputs and inputs,
2) **Lags** due to learning and adjustment,
3) **Redistribution** and dissipation of profits,
4) **Mismanagement** of information and technology.

The first two explanations point to shortcomings in research, not practice, as the root of the productivity paradox. It is possible that the benefits of IT investment are quite large, but that a proper index of its true impact has yet to be identified. *Traditional* measures of the relationship between inputs and outputs fail to account for *non-traditional* sources of value. Second, if significant lags between cost and benefit exist, then poor short-term performance could ultimately result in proportionately larger long-term pay-offs. This would be the case if extensive learning by both individuals and organizations were required to fully exploit IT, as it is for most radically new technologies.

[27] Hitt and Brynjolfsson (1994) suggest the fiercer competition hypothesis: "creating value and destroying profit." If barriers to entry have been lowered by various factors including the broad effects of IT, the profits will be destroyed. Another possible explanation is the hidden adjustment costs of IT: while IT's contribution to output is substantial, significant hidden costs of IT destroy profit. The adjustment cost hypothesis also explains the large ROI differentials between IT and non-IT capital and the large marginal rate of substitution between IS and non-IS workers.
[28] Robert M. Solow, in a comment of Landauer's [1995] book.

A more pessimistic view is embodied in the other two explanations. They propose that there really are no major benefits, now or in the future, and seek to explain why managers would systematically continue to invest in information technology. The redistribution argument suggests that those investing in the technology benefit privately but at the expense of others, so no net benefits show up at the aggregate level. The final explanation suggests that we have systematically mismanaged information technology: there is something in its nature that leads firms or industries to invest in it when they shouldn't, to misallocate it, or to use it to create slack instead of productivity. This section assesses each of these four sets of hypotheses in turn.

A. Measurement Errors

The easiest explanation for the confusion about the productivity of information technology is simply that we are not properly measuring output. Denison [1989] makes a wide-ranging case that productivity and output statistics can be very unreliable. Most economists would agree with the evidence presented by Gordon and Baily [1989], and Noyelle [1990] that the problems are particularly bad in service industries, which happen to own the majority of information technology capital. Griliches et al. [1992] present extensive studies on this problem with an especially useful introduction. Quick reviews of this type of argument are also found in Griliches [1994, 1995].

It is important to note that measurement errors need not necessarily bias IT productivity if they exist in comparable magnitudes both before and after IT investments. However, the sorts of benefits that managers ascribe to information technology—increased quality, variety, customer service, speed and responsiveness—are precisely the aspects of output measurement that are poorly accounted for in productivity statistics as well as in most firms' accounting numbers[Brynjolfsson, 1994]. This can lead to systematic underestimates of IT productivity.

The measurement problems are particularly acute for IT use in the service sector and among white collar workers. Since the null hypothesis that no improvement occurred wins by default when no *measured* improvement is found, it probably is not coincidental that service sector and information worker productivity is considered more of a problem than manufacturing and blue collar productivity, where productivity measurement is better.

As discussed in the introduction, when comparing two output levels, it is important to deflate the prices so that they are comparable in “real” dollars. Accurate price adjustment should remove not only the effects of inflation but also adjust for any quality changes. Much of the measurement problem arises from the difficulty of developing accurate, quality-adjusted price deflators. Additional problems arise when new products or features are introduced, not only because they have no predecessors for direct comparison, but also because variety itself has value, and that can be nearly impossible to measure.

The positive impact of information technology on product variety and the negative impact of product variety on measured productivity has been econometrically and theoretically supported by Brooke [1992]. He argues that lower costs of information processing have enabled companies to handle more products and more variations of existing products. However, the increased scope has been purchased at the cost of reduced economies of scale and has therefore resulted in higher unit costs of output. For example, if a clothing manufacturer chooses to produce more colors and sizes of shirts, which may have value to consumers, existing productivity measures rarely account for such value and will typically show higher “productivity” in a firm that produces a single color and size.[29]

Diewert and Smith’s [1994] study makes another interesting point in respect to variety, linking firm-level performance and aggregate economy. They show that IT facilitates great efficiency in inventory management. On the other hand, aggregate level inventory studies such as Blinder and Maccini’s [1991] report that the aggregate inventory level of the US economy did not shrink for 40 years. Diewert and Smith argue that “a wide spread proliferation of new products

[29] The same phenomenon suggests that much of the initial decline in “productivity” experienced by centrally-planned economies when they liberalize is spurious [Joskow, Schmalensee and Tsukanova, 1994].

into the world economy" results in no macro-level inventory change even when great micro-level improvements have been made.

In services, the problem of unmeasured improvements can be even worse than in manufacturing. For instance, the convenience afforded by twenty-four hour ATMs is frequently cited as an unmeasured quality improvement [Banker and Kauffman, 1988]. How much value has this contributed to banking customers? Government statistics implicitly assume it is all captured in the number of transactions, or worse, that output is a constant multiple of labor input! [Mark, 1982]

In a case study of the finance, insurance and real estate sector, where computer usage and the numbers of information workers are particularly high, Baily and Gordon [1988] identified a number of practices by the Bureau of Economic Analysis (BEA) which tend to understate productivity growth. Their revisions add 2.3% per year to productivity between 1973 and 1987 in this sector.[30]

Gordon [1987a] shows that the sectors where the productivity slowdown has persisted in the United States are largely outside of manufacturing, communications, and agriculture. Griliches [1994] provides a lucid example of the mismeasurement explanation. According to this review, "The major answer to this puzzle is very simple: over three quarters of this investment has gone into our 'unmeasurable sectors,' and thus its productivity effects, which are likely to be quite real, are largely invisible in the data." (See Table 4.)

A related measurement issue involves measuring information technology stock itself. For any given amount of output, if the level of IT stock used is overestimated, then its unit productivity will appear to be less than it really is. Denison [1989] argues that the rapid decreases in the real costs of computer power are largely a function of general "advances in knowledge" and as a result, the government overstates the decline in the computer price deflator by attributing these advances to the producing industry. If this is true, the "real" quantity of computers purchased recently is not as great as statistics show, while the "real" quantity purchased 20 years ago is higher. The net result is that much of the productivity improvement that the government attributes to the computer-*producing* industry, should be reallocated to computer-*using* industries. Effectively, computer users have been "overcharged" for their recent computer investments in the government productivity calculations.

Another issue is the measurement of other inputs. If the quality of work life is improved by computer usage (less repetitive retyping, tedious tabulation and messy mimeos), then theory suggests that proportionately lower wages can be paid. Thus the slow growth in clerical wages may be an artifact of unmeasured improvements in work life that are not accounted for in government statistics. Baily and Gordon [1988] conjecture that this may also be adding to the underestimation of productivity. Landauer [1995] also surmises people use computers because it is fun to use them.

To the extent that complementary inputs, such as software, or training, are required to make investments in information technology worthwhile, labor input may also be overestimated. Although spending on software and training yields benefits for several years, it is generally expensed in the same year that computers are purchased, artificially raising the short-term costs associated with computerization. In an era of annually rising investments, the subsequent benefits would be masked by the subsequent expensing of the next, larger, round of complementary inputs. On the other hand, IT purchases may also create long-term liabilities in software and hardware maintenance that are not fully accounted for, leading to an underestimate of IT's impact on costs.

The closer one examines the data behind studies of IT performance, the more it looks like mismeasurement , especially output mismeasurement, is at the core of the "productivity paradox." Rapid innovation has made information technology-intensive industries particularly

[30] They also add 1.1% to productivity growth before 1973.

susceptible to the problems associated with measuring quality changes and valuing new products. The way productivity statistics are currently kept can lead to bizarre anomalies: to the extent that ATMs lead to fewer checks being written, they can actually lower productivity statistics. Increased variety, improved timeliness of delivery and personalized customer service are other benefits that are poorly represented in productivity statistics. These are all qualities that are particularly likely to be enhanced by information technology. Because information is intangible, increases in the implicit information content of products and services are likely to be under-measured compared to increases in materials content.

Many economists have tried to tackle these types of problems. The long history of the hedonic price method is a good example of their efforts.[31] As a result of endeavors of econometricians, the Bureau of Economic Activity introduced a new computer price index, based on the hedonic regression method in 1986.[32] Gordon [1987b] reports that about one-third of the manufacturing sector's productivity gain during the eighties comes from this adjustment alone. Since the computer industry does not monopolize quality improvement over time, the application of the new technique to all national income accounts would make a sizable difference.

Some researchers argue that even the hedonic regression method is not sufficient to 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. In the case of the computed tomography scanner industry for the period of 1973-1982, Trajtenberg's price deflator averages minus 55%, while the hedonic price index shows only a 13% decline and government price statistics indicate a 9% increase. 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 Bureau of Labor Statistics will seriously overestimate inflation. The empirical evidence for their argument is given in Griliches and Cockburn [1994]. In a case of pharmaceutical price indices -- cephalexin price indices

31 See Berndt [1991] for a brief history of hedonic price method.

32 See Ellen Dulberger[1989]. Jack Triplett [1986, 1989] also provides historical background.

during the 1987-91 period, they show that adjusted price indices reveal a 30% to 53% drop while the official figure records a 14% increase. Hausman [1994] also reports a 20 - 25% overestimation of consumer price index in the case ready-to-eat cereals, based on his analysis of Apple Cinnamon Cheerios.

The story behind all these studies is that the U.S. economy produces lots of "unmeasurables" that official statistics do not capture. The question remains: why does this happen? Two possible complementary answers can be given. The first one is that unmeasurables are relatively price inelastic and income elastic. This is a demand-side explanation. As people become wealthier, they want more convenience, timeliness, variety, and quality as opposed to mere quantity. Now one can look at supply-side, too. The second hypothesis is that information technology is biased favorably toward unmeasurables: utilizing IT, it is much easier to increase product variety, timeliness, convenience, and customization than to make more things. The reason is very simple; unmeasurables are more information intensive and do not require material costs. As IT becomes cheaper, the prices of unmeasurables decline faster than those of measurables. The result is that people will buy more unmeasurables relative to measurables. International trade may mitigate this price disparity, since cheaper measurable goods can be bought abroad. However, the more goods are imported, the more domestic firms concentrate on producing unmeasurables. American managers' inclination toward the unmeasurables are reported by several studies. For example, Brynjolfsson [1994] documents that the top benefit managers expect from IT investment is improved customer service. Lowering costs is the next most important benefit, but they also stress timeliness of interactions with customers, higher product and service quality, support for reengineering efforts, and more flexibility.

One may test the demand side hypothesis by looking at foreign data. If the explanation is correct, one may expect IT effects on productivity to be captured more easily in developing countries than in high income countries. Poh-Kam Wong [1994] reports that in Singapore economy-wide estimation of return on investment of IT is 88%. Also in some developed countries like Japan where tradable sectors, which are also measurable sectors, remain strong, we may expect high measurable effects of IT. Kraemer and Dedrick [1994] find that, among 12 Pacific Rim countries, those with higher growth rates in IT investment achieved a higher growth rate of GDP and productivity for the 1984-1990 period.

Nonetheless, some analysts are skeptical that measurement problems can explain much of the slowdown. They point out that by many measures, service quality has gone down, not up.[33] Furthermore, they question the value of variety when it takes the form of six dozen brands of breakfast cereal. Indeed, models from industrial organization theory suggest that while more variety will result from the flexible manufacturing and lower search costs enabled by IT, the new equilibrium can exhibit *excess* variety, making consumers worse off [Tirole, 1988]. In addition, a study by Sichel [1995] casts doubt on Griliches' unmeasurable sector hypothesis, saying that the rising share of services has had only a small impact on measurement error.[34] Theses arguments suggest that the mismeasurement explanation is not the panacea for the productivity puzzle.

B. Lags

A second explanation for the paradox is that the benefits from information technology can take several years to appear on the bottom line. The idea that new technologies may have a delayed impact is a common one in business. For instance, a survey of executives suggested that many expected it to take as long as five years for information technology investments to pay off [Nolan/Norton, 1988]. This accords with an econometric study by Brynjolfsson et al. [1991] which found lags of two to four years before the strongest organizational impacts of information technology were felt. Loveman [1994] also found slightly higher, albeit still very low, productivity when small lags were introduced.

[33] Nordhaus in a comment on Baily and Gordon [1988] recalls the doctor's house call, custom tailoring, and windshield wiping at gas stations, among other relics.
[34] However, Sichel's study does not address the possibility that computers have reduced the measurability of output within sectors.

The existence of lags has some basis in theory. Because of the unusual complexity and novelty of IT, firms and individual users may require some experience before becoming proficient [Curley and Pyburn, 1982]. According to dynamic models of learning-by-using, the optimal investment strategy sets short term marginal costs greater than short-term marginal benefits. This allows the firm to "ride" the learning curve and reap benefits analogous to economies of scale [Scherer, 1980]. If only short-term costs and benefits are measured, then the investment might appear inefficient. Viewed in this framework, there is nothing irrational about the "experimentation" phase firms are said to experience in which rigorous cost/benefit analysis is not undertaken. Because future information technology investments tend to be large relative to current investments, the learning effect could be quite substantial. A similar pattern of costs and benefits is predicted by an emerging literature that treats investments in information technology as "options", with short term costs, but with the potential for long-term benefits [Kambil et al., 1991, and Dixit and Pindyck, 1995].

One way to address the measurement problem associated with complementary inputs is to introduce appropriate lags in the estimation procedure. For instance, the purchase of a mainframe computer must generally precede the development of mainframe database software. Software, in turn, usually precedes data acquisition. Good decisions may depend on years of acquired data and may not instantaneously lead to profits. Optimally, a manager must take into account these long-term benefits when purchasing a computer, and so must the researcher seeking to verify the benefits of computerization.

If managers are rationally accounting for lags, information technology productivity growth is particularly optimistic. In the future, we should reap not only the then-current benefits of the technology, but also enough additional benefits to make up for the extra costs we are currently incurring. However, the credibility of this explanation is somewhat undermined by the fact that

American managers have not been noted for long-term cost-benefit analysis.[35] More importantly, the uncertainties and the sharp price decline suggest another direction of investment behavior. The risk and uncertainty associated with new technologies can make risk-averse managers require higher, not lower, rates of return before they will invest. Also the sharp decline in computer prices will require higher user cost of IT capital, which leads to the opposite direction of investment behavior to learning-by-doing effects. In any case, it is hoped that increased familiarity, ease-of-use and end-user computing may lead to reduced lags between the costs and benefits of computerization. In addition, it should be noted that market value of firms would capture the lagged benefits of IT investment, when the stock market is efficient enough to take into account the long-term benefits of the investment.

C. Redistribution

A third possible explanation is that information technology may be beneficial to individual firms, but unproductive from the standpoint of the industry or the economy as a whole: IT rearranges the shares of the pie without making it any bigger.

There are several arguments for why redistribution may be more of a factor with IT investments than for other investments. For instance, information technology may be used disproportionately for market research and marketing, activities which can be beneficial to the firm while adding little to total output [Lasserre, 1988; Baily and Chakrabarti, 1988]. Furthermore, economists have recognized for some time that, compared to other goods, information is particularly vulnerable to rent dissipation, in which one firm's gain comes at the expense of others, instead of by creating new wealth. As Hirshleifer [1971] pointed out, advance knowledge of demand, supply, weather or other conditions that affect asset prices can

[35] See, for example, Stein's [1989] interesting application of a signal jamming model, which reveals the possibility of ineffective stock incentives. His model shows even when the stock incentive system is applied, in equilibrium managers still forsake good investments so as to boost current earnings.

profit private firms without increasing total output. This will lead to excessive incentives for information gathering.

In a similar spirit, "races" to be the first to apply an innovation can also lead to rent dissipation [Fudenberg and Tirole, 1985]. The rapid-fire pace of innovation in the information technology industry might also encourage this form of wasteful investment. Baily and Chakrabarti [1988] run a simulation under the assumption that a major share of the private benefits of information technology result from redistribution. The results are broadly consistent with the stylized picture of increased information technology and workers without increases in total productivity. Bresnahan, Milgrom, and Paul [1992], in a paper measuring "real output" of the stock exchange industry, propose an interesting argument: the stock exchange industry has grown thanks to information technology, yet the new information gathered by the industry has contributed little to social product. It is interesting to note that most of the reasons for investing in information technology given by the articles in the business press involve taking profits from competitors rather than lowering costs.[36]

While redistribution implies overinvestment in IT, some researchers look at the possibility of positive externalities that may lead to less than social optimum investment. Bresnahan and Trajtenberg [1995] propose two types of positive externalities -- vertical and horizontal externalities which a "general purpose technology sector" may face. The vertical externality is a familiar problem of appropriability. Since it is difficult for innovators to reap the benefits, they are reluctant to invest. Pamela Samuelson et al. [1994] enumerate reasons why the conventional legal tools fail to protect information technology innovation. In addition, the horizontal externality exists because firms are waiting for other firms to invest. The more other firms invest, the faster the speed of innovation in the general purpose technology sector. Knowing that, everyone waits; investments are too small and innovation is too slow.

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36 Porter and Miller, 1985, is not atypical. They emphasize "competitive advantage" gained by changes in industry structure, product and service differentiation and spawning of new businesses while devoting about 5% of their space to cost savings enabled by IT.

D. Mismanagement

Despite the evidence of positive productivity contributions, it is still possible that many IT investments are wasteful. The investments are made nevertheless because the decision-makers aren't acting in the interests of the firm. Instead, they are a) increasing their slack, b) signaling their prowess or c) simply using outdated criteria for decision-making.

Many of the difficulties that researchers have in quantifying the benefits of information technology would also affect managers [Baily, 1986a; Gremillion and Pyburn, 1985]. As a result, they may have difficulty in bringing the benefits to the bottom line if output targets, work organization and incentives are not appropriately adjusted [McKersie and Walton, 1991]. The result is that information technology might increase organizational slack instead of output or profits. This is consistent with arguments by Roach [1989a] that manufacturing has made better use of information technology than has the service sector because manufacturing faces greater global competition, and thus tolerates less slack.

A related argument emerges from evolutionary models [Nelson, 1981]. The difficulties in measuring the benefits of information and information technology discussed above may also lead to the use of heuristics, rather than strict cost/benefit accounting to set investment levels.[37] Our current institutions, heuristics and management principles evolved in a world with little information technology. The radical changes enabled by information technology may render these institutions outdated. For instance, a valuable heuristic in 1960 might have been "get all readily available information before making a decision." The same heuristic today could lead to information overload and chaos [Thurow, 1987]. Indeed, Ayres [1989] argues that the speed-up enabled by information technology creates unanticipated bottlenecks at each human in the

[37] Indeed, a review of the techniques used by major companies to justify information technology investments [Yamamoto, 1991] revealed surprisingly little formal analysis. See Clemons [1991] for an assessment of the IT justification process.

information processing chain. More money spent on information technology won't help until these bottlenecks are addressed.

At a broader level, several researchers suggest that our current low productivity levels are symptomatic of an economy in transition, in this case to the "information era" [Simon,1987; Franke, 1987; David 1990]. For instance, David makes an analogy to the electrification of factories at the turn of the century. It took twenty years for major productivity gains to emerge, when new factories were designed and built to take advantage of electricity's flexibility which enabled machines to be located based on work-flow efficiency, instead of proximity to waterwheels, steam-engines and power-transmitting shafts and rods.

While the idea of firms consistently making inefficient investments in IT is anathema to the neoclassical view of the firm as a profit-maximizer, it can be explained by formal models based on agency theory or evolutionary economics, which treat the firm as a more complex entity. The fact that firms continue to invest large sums in the technology suggests that individuals within the firm who make investment decisions benefit or at least believe that they benefit from IT.

For instance, a model of how IT enables managerial slack can be developed using agency theory. The standard result in this literature is that when managers' (agent) incentives are not aligned with shareholder (principal) interests, suboptimal investment decisions and effort can result. Furthermore, the incentives for agents to acquire additional information may exceed the social benefits. This is because agents can use the information to earn rents and to short-circuit the incentive scheme [Brynjolfsson, 1991]. Thus, information technology investments may be very attractive to managers even when they do little to boost productivity. To the extent that competition reduces the scope for managerial slack, the problem is alleviated. In general, however, we do not yet have comprehensive models of the internal organization of the firm and researchers, at least in economics, are mostly silent on the sorts of inefficiency discussed in this section.

One empirical implication of firm-level mismanagement may be the heterogeneous performance of firms. One perspective on firm differentials is present in Figure-7. According to neoclassical assumptions of investment, market value added should be around zero (type-B). Yet the figure shows that, among big IT investors, some firms perform better (type-A) while some other firms fail on a large scale (type-C). Indeed, as discussed earlier, Brynjolfsson and Hitt [1995] attribute as much as half of IT benefits to the firm specific effects. An earlier study by Kemerer and Sosa [1991] also suggests that firm performances are quite heterogeneous.

V. Conclusion

A. Summary

Research on information technology and productivity has often raised frustrating concerns with the measures and methods commonly used for productivity assessment. Recently, researchers have developed new data and methodologies, and at the same time have begun to report IT's positive effects on economic performance. Yet many puzzles remain unsolved, and we can not proclaim the end of the productivity paradox. This section summarizes our review, and suggests further research questions and methodologies.

Section II started with presenting a review of the principal empirical literature that engendered the term "productivity paradox". Looking at the simple relationship between the productivity slowdown of the whole US 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 development of sounder methodologies and the identification of more reliable and larger datasets, 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 exercises suggest that without IT the US economy would probably be in a worse situation.

While these findings represent a turnaround, we have yet to address many aspects of the "remaining paradox." While a few studies have identified a multifactor productivity boost due to IT, there is little evidence of a positive contribution from IT to other performance measures such as profit and market value. Section III considered explanations for the remaining paradox. Four hypotheses are summarized below.

1. Measurement Error: Outputs (and inputs) of information-using industries are not being properly measured by conventional approaches.

2. Lags: Time lags in the pay-offs of information technology make analysis of current costs versus current benefits misleading.

3. Redistribution: Information technology is especially likely to be used in redistributive activities among firms, making it privately beneficial without adding to total output.

4. Mismanagement: The lack of explicit measures of the value of information make it particularly vulnerable to misapplication and overconsumption by managers.

Of these, an examination of the principal studies and the underlying data underscores the possibility that measurement difficulties may account for the lion's share of the gap between our expectations for the technology and its apparent performance.

B. Where Do We Go from Here

1. Recommendations for Further Research

All four of the explanations for the remaining productivity paradox are still likely to be empirically important to some extent and future studies should test for them.

The first priority must be improving the data and 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 undertake original data gathering themselves. When the third option is pursued, it is important that the data be made available for use by 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.

An effective strategy for identifying gaps in the data is to compare it with benefits that managers and customers expect from IT, such as quality, timeliness, customer-service, flexibility, innovation, customization and variety. In principal, many of these benefits are quantifiable. In fact, the capital budgeting and justification process is one place in which firms already attempt such an analysis. In addition, many companies have already developed elaborate measurement programs, as part of total quality management for instance, which augment or even supersede financial accounting measures and can serve as a foundation for more refined metrics.

Unfortunately, for many services, even basic output measures still need to 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, memoranda 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 rigorously measure productivity of services 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.

Correcting for the potential lags in the impact of IT is conceptually easier. All that needs to be done is to include lagged values of IT in the regression. Of course, because learning and adjustment may take five or more years [Brynjolfsson et al., 1991], this presupposes that a sufficiently long sample can be obtained. Depending on the assumptions made about the nature of adjustment costs, including lagged values of the dependent variable may also be appropriate, although this can introduce complications when serial correlation is present. In a structural model, there is some potential for examining adjustment costs even with cross-sectional samples. For instance, if software spending generally peaks after hardware spending, then their ratio can be an indicator of the relative stage of the investment cycle of the firm, with implications for the timing and level of expected benefits. [38]

Because so many other factors affect firm performance, it will generally be impossible to distinguish the impact of IT from simple bivariate correlations. It is essential to include controls for other factors such as other inputs and their prices, the macro-economic environment, demand schedules for output, and the nature of competition. Because many factors will be unobservable but will 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.

The redistribution hypothesis can be examined in two ways. If IT spending serves mainly to take market share from competitors, but the resulting profits are quickly dissipated or transferred to the customer, then profitability or even revenues may not be a good indicator of IT's impact. Instead, a regression using market share as the dependent variable will be a better

[38] Interestingly, firms that spend proportionately more money on software appear to be more profitable [Computer Economics Report, 1988]. If firms go through a hardware buying phase followed by an applications phase, then this may have more to due with firms being in different stages of a multi-year process than with different technology strategies.

indicator. This is especially true when intangibles associated with the output of the firm (e.g. customer service and quality) are not easily captured in traditional measures but do influence the customer's purchase decision.[39]

A second technique is to compare various measures of a firm's performance with its *competitors'* IT spending. Under the above assumptions, the coefficient should be negative. The coefficient will also be negative when IT serves to increase the efficiency of the market, for instance by reducing search costs, and thereby reducing the market power of suppliers and the potential for pricing above marginal cost. As Bakos [1987] has shown, competitors may be collectively better off if such systems are not introduced, but each has an individual incentive to pre-empt the others. There is evidence that this phenomenon may have been important in the financial services industry in the 1980s [Steiner and Teixeira, 1991].

To address the mismanagement hypothesis, we need to develop and introduce better theoretical models. While there is a great deal of anecdotal evidence for misuses of technology in organizations, more rigorous explanations are needed to show how and why IT might be subject to systematic overinvestment or mistakes in implementation. Among the more promising approaches is the development of better models that analyze the demand for information. Preliminary work suggests that under reasonable assumptions, agents may have an overincentive to acquire and process information [Brynjolfsson, 1989]. Signaling models, that formalize use of IT as a non-productive, but individually valuable, symbol of managerial or technological prowess, also appear to be a natural next step. A better theoretical foundation for the mismanagement hypothesis will enable order-of-magnitude estimates that will help identify which explanations are likely to be empirically significant, and will facilitate the testing of these explanations by identifying the relevant variables and relationships.

39 In a double-log specification of the conventional production function approach, including industry dummies capture the same effect, provided that the industries are the markets where firms actually compete. The main difficulty of the market share approach comes from the ambiguous definition of market and data.

Finally, even with these substantive improvements in our research on IT and productivity, we must not overlook that fact that our tools are still blunt. Managers do not always recognize this and tend to give a great deal of weight to studies of IT and productivity. The studies themselves are usually careful to spell out the limitations of the data and methods, because they are written for an academic audience, but sometimes only the surprising conclusions are reported by the media. Because significant investment decisions are based on these conclusions,[40] researchers must be doubly careful to communicate the limitations of their work.

2. Beyond Productivity and Productivity Measurement

While the focus of this paper has been on the productivity literature, in business-oriented journals a recurrent theme is the idea that information technology will not so much help us produce more of the same things as allow us to do entirely new things in new ways [Applegate and Mills, 1988; Benjamin et al., 1984; Cecil and Hall, 1988; Hammer, 1990; Malone and Rockart 1991; Porter and Miller, 1985; Watts, 1986]. 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, while Brooke [1992] makes a connection to greater variety but lower productivity as traditionally measured. The business transformation literature highlights how difficult and perhaps inappropriate it would be to try to translate the benefits of information technology usage 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 quality 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's [1995] recent argument is suggestive: "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."

[40] 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, 1991].

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 of a product are generally assumed to be in the best position to assess the utility they gain from their purchases, one might naturally look to IT buyers for an estimate of IT value as Bresnahan [1986] and Brynjolfsson [1995] did.

A second alternative to traditional productivity measures is to look at stock market data. If one assumes that rational investors will 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, and quality, and in principle, even the effectiveness of the firm in foreseeing and rapidly adapting to its changing environment.[41] 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].

If the value of IT remains controversial, the one certainty is 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.[42] The comparison of the emerging "information age" to the industrial revolution has prompted a new approach to management accounting [Beniger, 1986; Kaplan, 1989]. A review of the IT productivity research indicates an analogous opportunity to rethink the way we measure productivity and output.

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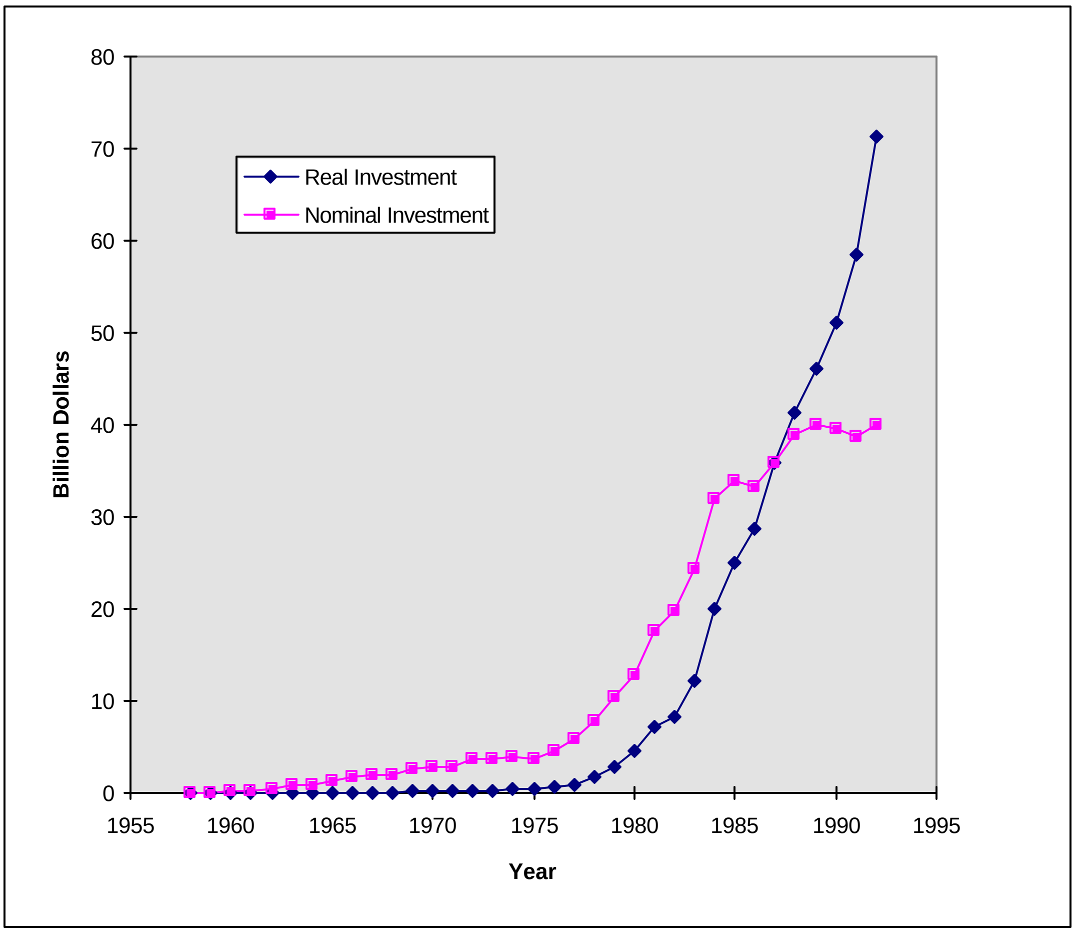
41 Unfortunately, stock market valuation also reflects the firm's relative market power, so where IT leads to more efficient markets or greater *customer* bargaining power, the relationship between IT and stock price is ambiguous.

42 A look at the BEA's SIC codes quickly reveals that manufacturing is classified in relatively rich detail while only the broadest measures exist for services, which comprise over 80% of the economy.

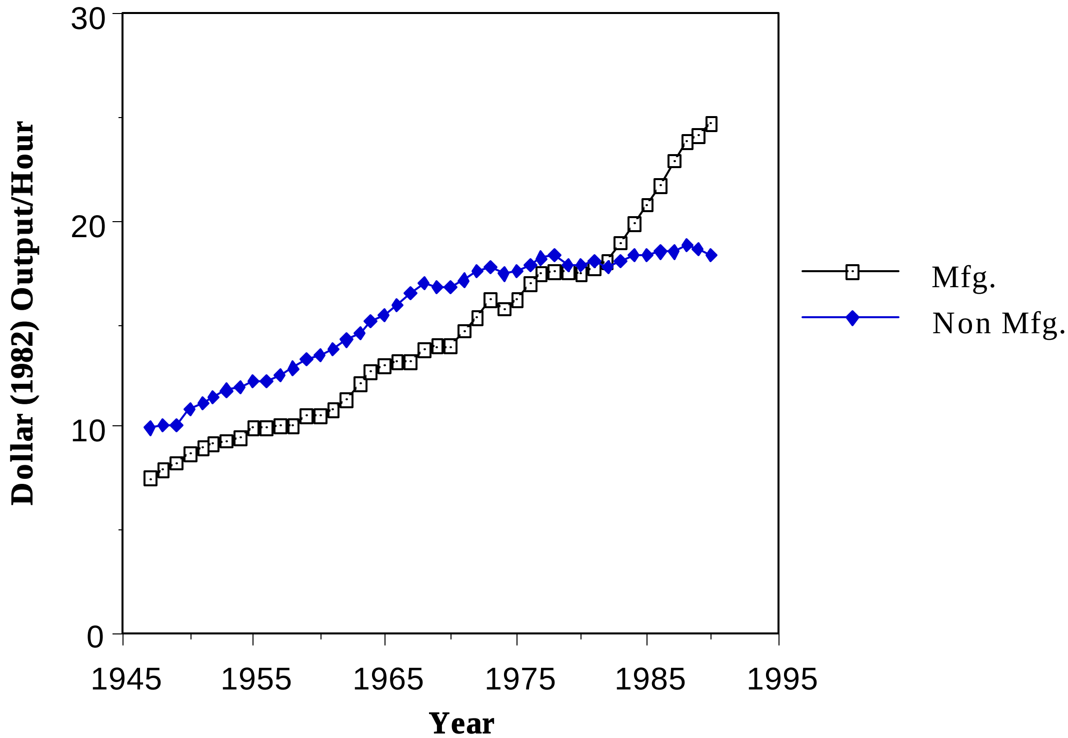
Figures

Figure 1 -- Investment in information technology is growing at a rapid pace.



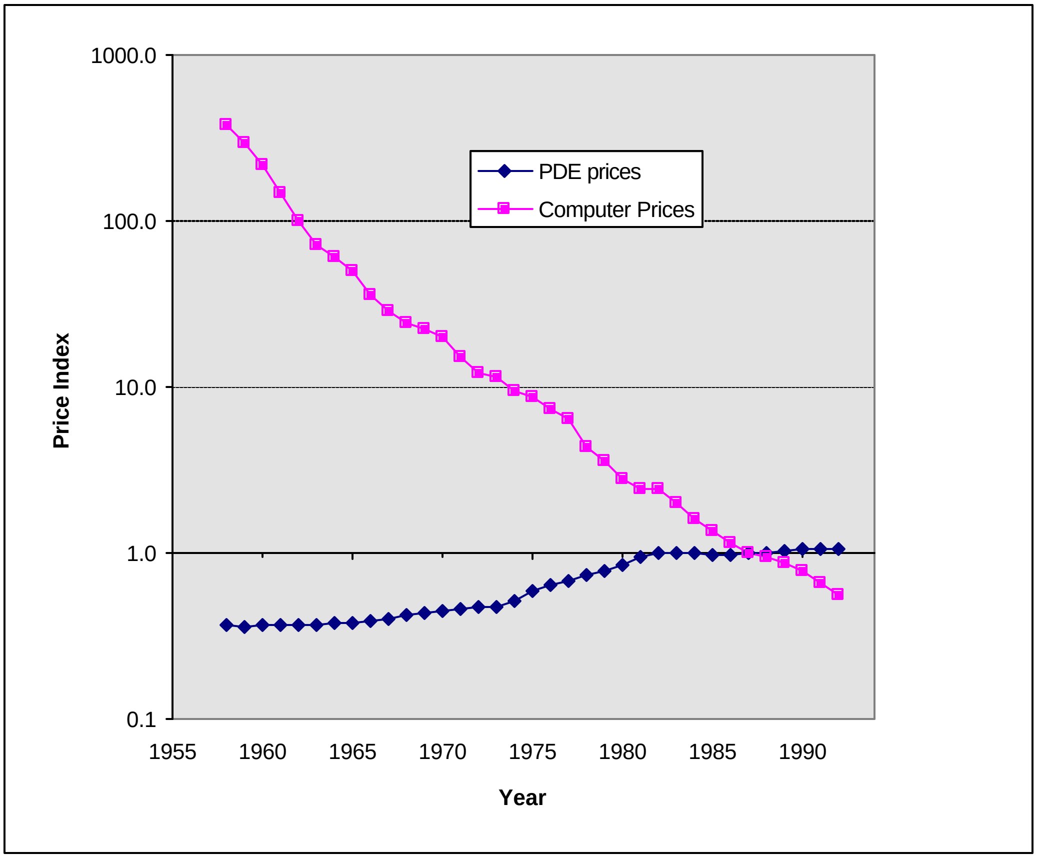
Source: Based on data from [BEA, National Income and Wealth Division], adapted from Jorgenson and Stiroh [1995].
Note: Constant dollars (base year 1987) calculated by hedonic price method, see Dulberger [1989].

Figure 2 -- Productivity in the service sector has not kept pace with that in manufacturing.



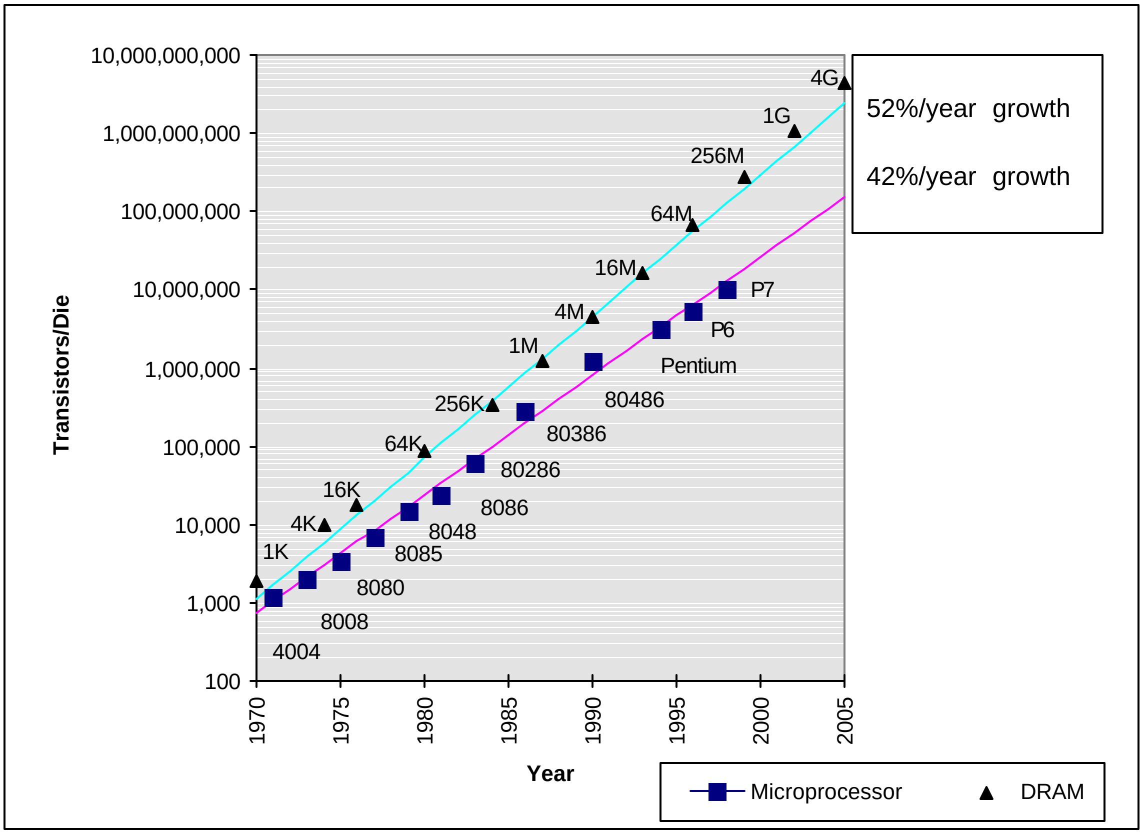
Source: Based on data from [Bureau of Labor Statistics, Productivity & Testing]

Figure 3a—The cost of computing has declined substantially relative to other capital purchases.



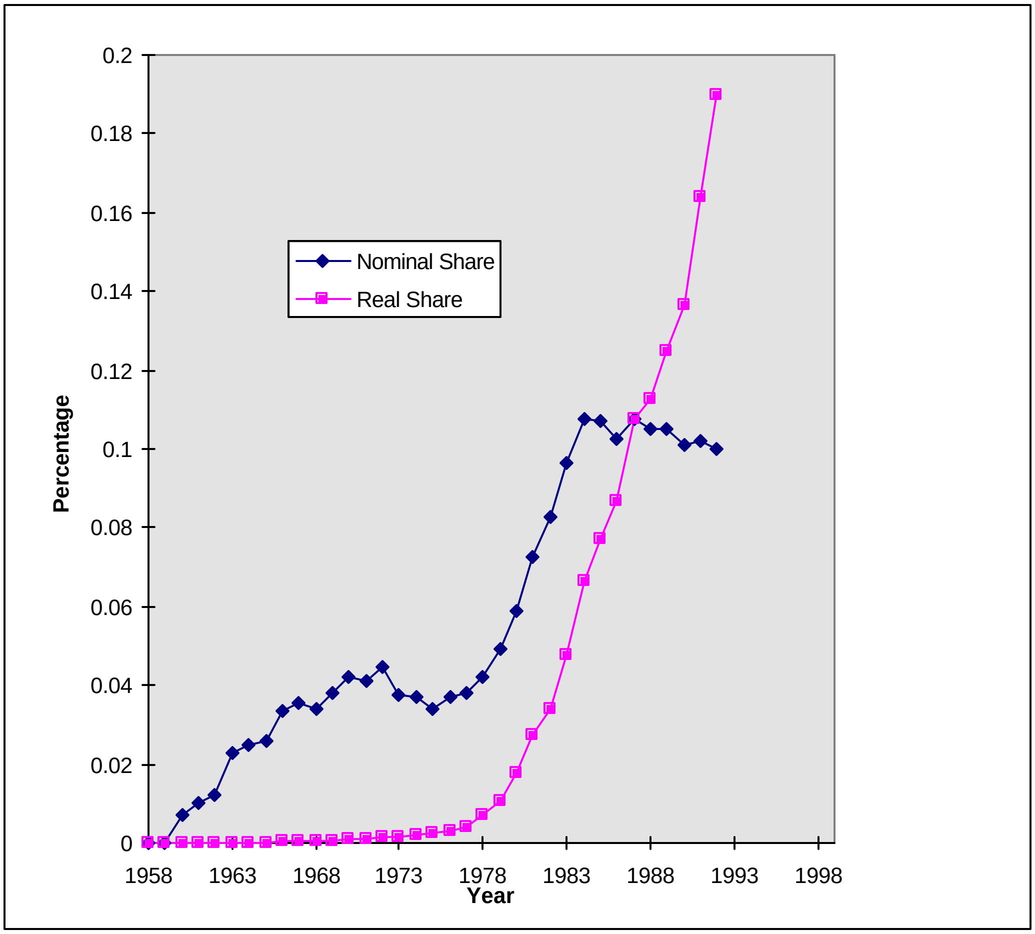
Source: Based on data from [U.S. Dept. of Commerce, Survey of Current Business]
Note: PDE, Producer's Durable Equipment

Figure 3b—Microchip performance has shown uninterrupted exponential growth.



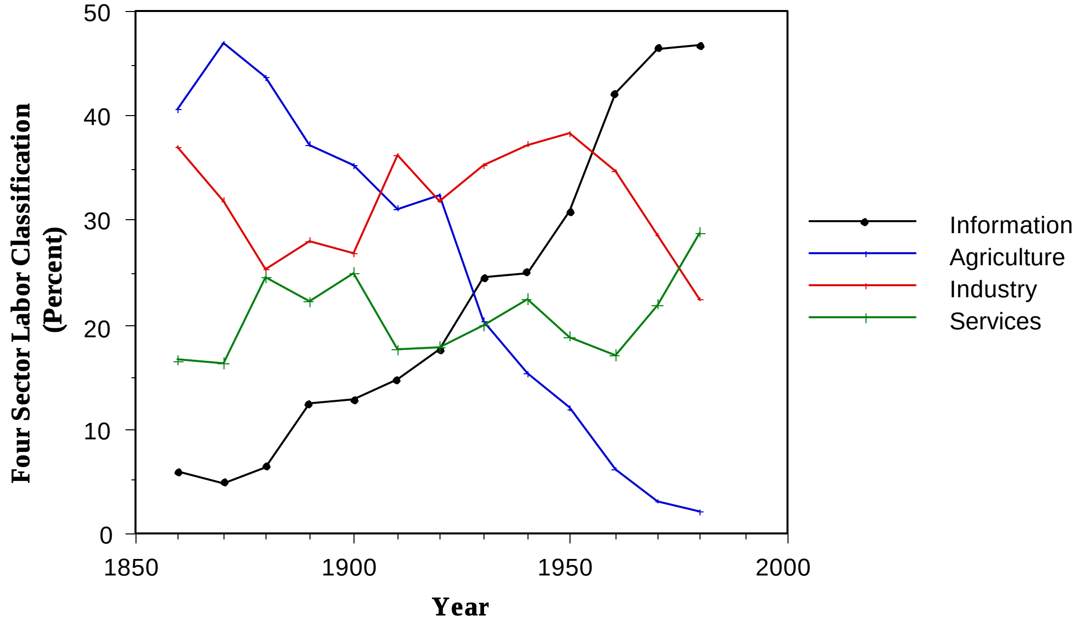
Source: Grove [1990], and company data. Trend lines are by authors' estimation.
Note: P6, P7 microprocessors and 256M, 1G, 4G DRAMs are estimated by Intel and Semiconductor Industry Association.

Figure 4 -- Computers comprise about 10% of current-dollar investment in Producers' Durable Equipment



Source: Based on data from [BEA, National Income and Wealth Division]

Figure 5 -- Information processing is the largest category of employment.



Source: Porat [1977]. The defining criterion for information workers is whether the primary activity is knowledge creation, warehousing, or dissemination. An classification scheme includes people engaged in the following activities:

TYPOLOGY OF PRIMARY INFORMATION SECTOR INDUSTRIES USED IN FIGURE 5

KNOWLEDGE PRODUCTION AND COMMUNICATION INDUSTRIES
- R&D and Inventive Industries
- Private Information Services

INFORMATION DISTRIBUTION AND COMMUNICATION INDUSTRIES
- Education
- Public Information Services
- Regulated Communication Media
- Unregulated Communicated Media

RISK MANAGEMENT
- Insurance Industries
- Finance Industries
- Speculative Brokers

SEARCH AND COORDINATION INDUSTRIES
- Search and Non-Speculative Brokerage Industries
- Advertising Industries
- Non-Market Coordination Institutions

INFORMATION PROCESSING AND TRANSMISSION SERVICES
- Non-Electronic Based Processing
- Electronic Based Processing
- Telecommunications Infrastructure

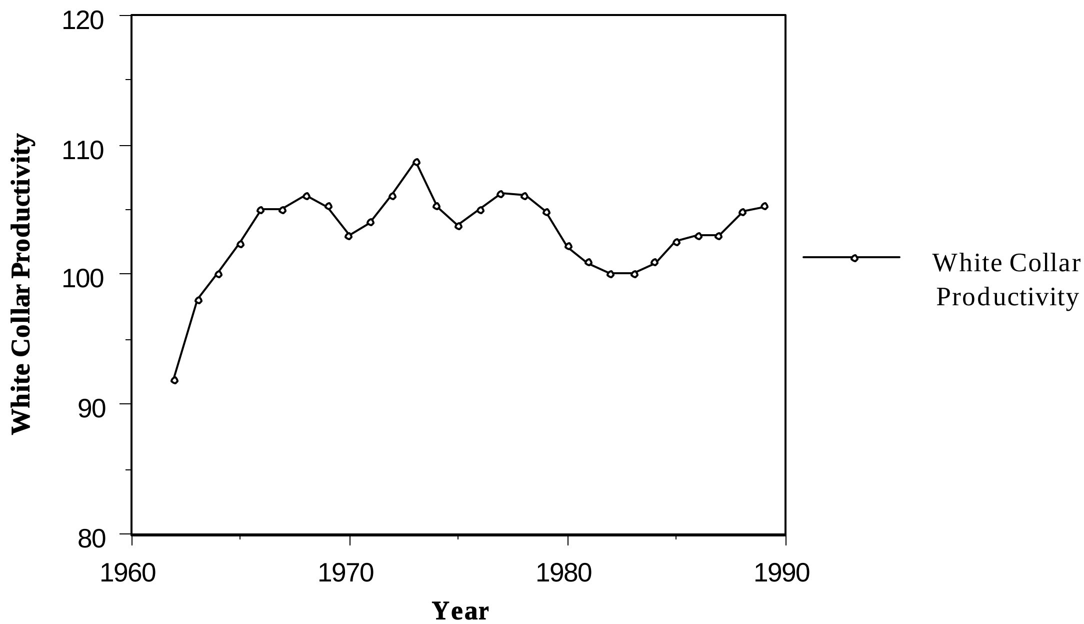
INFORMATION GOODS INDUSTRIES
- Non-Electronic Consumption or Intermediate Goods
- Non-Electronic Investment Goods
- Electronic Consumption or Intermediate Goods
- Electronic Investment Goods

SELECTED GOVERNMENT ACTIVITIES
- Primary Information Services in the Federal Government
- Postal Service
- State and Local Education

SUPPORT FACILITIES
- Information Structure Construction and Rental

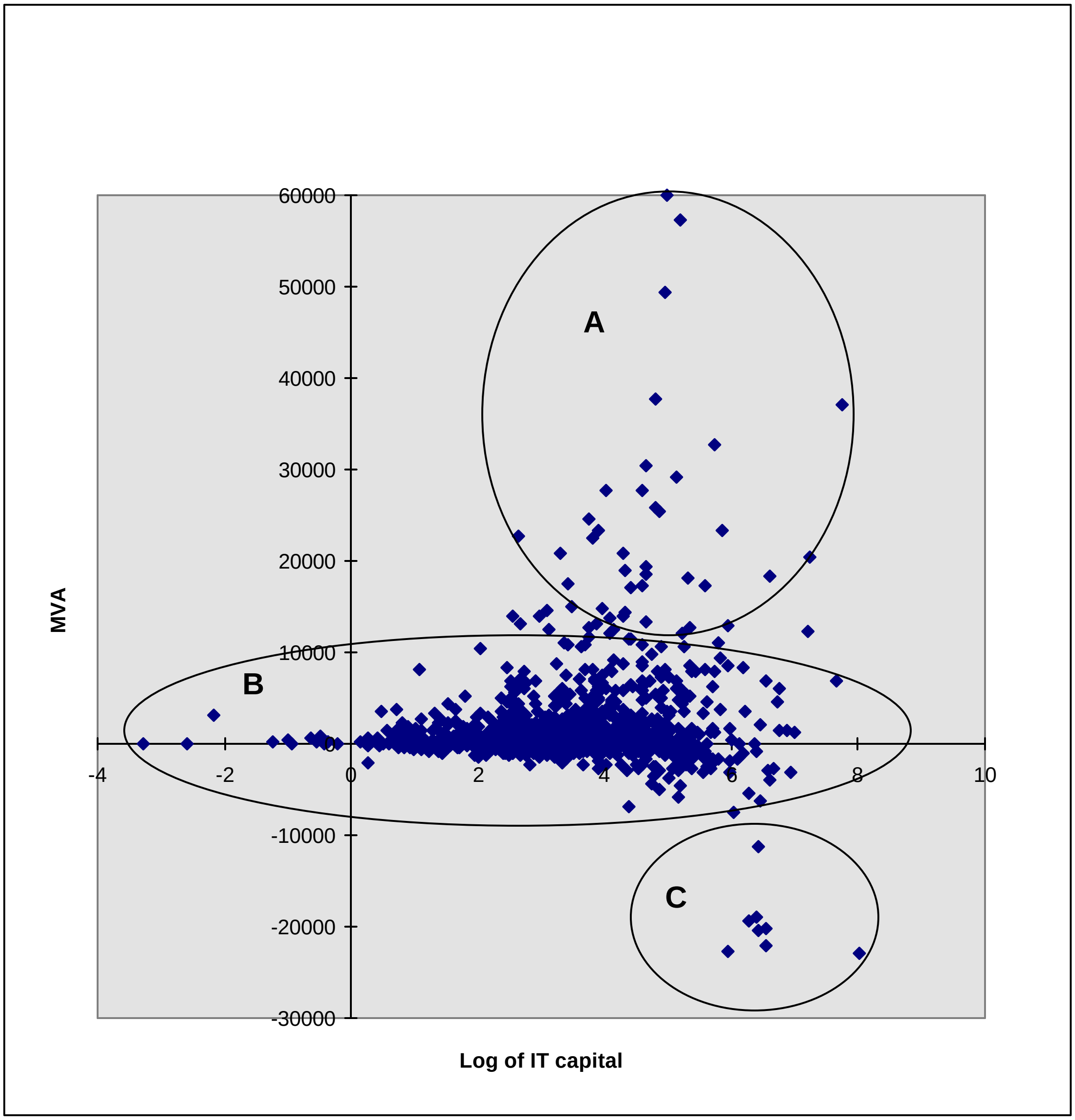
Office Furnishings

Figure 6 -- White collar productivity appears to have stagnated.



Source: Roach [1991]

Figure 7 -- Firm performances are heterogeneous: Market value added IT Capital, for Fortune 500 firms



Source: Brynjolfsson and Hitt [1993] and Stern Stewart Management Services [1994].

Bibliography

Ahituv, N. and Giladi, N. [1993], "Business Success and Information Technology: Are They Really Related," Proceedings of the 7th Annual Conference of Management IS, Tel Aviv University.

Allen, Thomas J. and Scott Morton, Michael 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, Fall, 7(2): 55-69.

Alpar, P. and Kim, M. [1990], "A Comparison of Approaches to the Measurement of Information Technology Value," Proceedings of the 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, Vol. 27:1184-1192, (December).

Ayres, R. U. [1989], "Information, Computers, CIM and Productivity," Organization for Economic Co-operation and Development Paper, (June).

Baily, Martin Neil [1986a], "Taming the Information Monster," Bell Atlantic Quarterly, Summer, pp. 33-38.

Baily, Martin Neil [1986b], "What Has Happened to Productivity Growth?" Science, Vol. 234: 443-451.

Baily, Martin Neil and Chakrabarti, A. [1988], "Electronics and White-Collar Productivity," in Innovation and Productivity Crisis, Brookings, Washington.

Baily, Martin Neil and Gordon, R. J. [1988], "The Productivity Slowdown, Measurement Issues and the Explosion of Computer Power", Brookings Papers in Economic Activity, 1988(2): 347-431.

Bakos, J. Yannis [1987], Inter-organizational Information Systems: Strategic Implications for Competition and Cooperation, Ph.D. Dissertation, MIT School of Management.

Bakos, J. Yannis and Kemerer, Chris F. [1992], "Recent Application of Economic Theory in Information Technology Research," Decision Support System Vol. 8: 365-386.

Banker, R. D. and Kauffman, R. J. [1988], "Strategic Contributions of Information Technology: An Empirical study of ATM Networks," Proceedings of the 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): 415-26

Baumol, W.J., S. A. Blackman, and E. N. Wolff. [1985], "Unbalanced Growth Revisited: Asymptotic Stagnancy and New Evidence," American Economic Review 74(4): 806-17

Bender, D. H. [1986], Financial Impact of Information Processing. Vol. 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 Manufactures,” Quarterly Journal of Economics, Vol. 109(2): 367-397.

Berndt, Ernst R. [1991], The Practice of Econometrics: Classic and Contemporary, Addison-Wesley, Reading, MA.

Berndt, Ernst R. and Malone, Thomas 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, Vol. 3: 177-182.

Berndt, Ernst R. and Morrison, Catherine J. [1995], “High-tech Capital Formation and Economic Performance in U.S. Manufacturing Industries: An Exploratory Analysis”, Journal of Econometrics 65: 9-43.

Berndt, Ernst R. and Morrison, Catherine J. [1991], “Computers Aren’t Pulling Their Weight,” Computerworld, December 9, pp. 23-25.

Berndt, Ernst R., Morrison, Catherine J. and Rosenblum, Larry 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 L.J. Maccini [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, Vol. 105: 19-27, (December).

Bresnahan, Timothy F. [1986], “Measuring Spillovers from Technical Advance: Mainframe Computers in Financial Services,” American Economic Review 76(4), (September).

Bresnahan, Timothy F., Milgrom, Paul and Paul, Jonathan [1992], “The Real Output of the Stock Exchange,” in Griliches et al. (Ed.), Output Measurement in the Service Sectors, University of Chicago Press.

Bresnahan, Timothy 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, Erik [1995], “Some Estimates of the Contribution of Information Technology to Consumer Welfare,” MIT Sloan School of Management Working Paper, (August).

Brynjolfsson, Erik [1994], “Technology’s True Payoff,” Informationweek, October 10, pp. 34-36.

Brynjolfsson, Erik [1991], “Information Technology and the New Managerial Work,” MIT Sloan School of Management Working Paper No. 3563-93, (March).

Brynjolfsson, Erik [1989], “The Value of Information in an Agency Setting: When ignorance is Bliss,” unpublished paper, (June).

Brynjolfsson, Erik and Hitt, Lorin. [1995], “Information Technology as a Factor of Production: the Role of Differences among Firms,” Economics of Innovation and New Technology, Vol. 3: 183-199.

Brynjolfsson, Erik and Hitt, Lorin. [1994], “Computers and Economic Growth: Firm-Level Evidence,” MIT Sloan School of Management Working Paper No. 3714, (August).

Brynjolfsson. Erik and Hitt, Lorin. [1993], “Is Information Systems Spending Productive? New Evidence and New Results”, The Proceedings of the 14th International Conference on Information Systems, Orlando, FL.

Brynjolfsson, Erik, Malone, T. Gurbaxani, V., et al. [1991], “Does Information Technology Lead to Smaller Firms?” MIT Center for Coordination Science Technical Report No. 123, (September).

Champy, James [1995], Reengineering Management, HaperBusiness, New York, NY.

Cecil, J. L. and Hall, E. A. [1988], “When IT Really Matters to Business Strategy,” McKinsey Quarterly, pp. 2, (Autumn).

Chismar, W. G. and Kriebel, C. H. [1985], “A Method for Assessing the Economic Impact of Information Systems Technology on Organizations,” Proceedings of the Sixth International Conference on Information Systems, Indianapolis, Indiana.

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, Kevin and Malone, Thomas W. [1988], “Information Technology and Work Organization,” Chapter 49 in: M. Helander, ed., Handbook of Human-Computer Interactions. Elsevier Science, Amsterdam, pp. 1051-1070.

Crowston, Kevin 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, Thomas H. [1993], Process Innovation: Reengineering Work through Information Technology, Harvard Business School Press, Boston, Massachusetts.

Davenport, Thomas H. and Short, J. [1990], "The new Industrial Engineering: Information Technology and Business Process Redesign," Sloan Management Review, Vol. 31(4): 11-27.

David, Paul A. [1990], "The Dynamo and the Computer and Dynamo: A Historical Perspective on the Modern Productivity Paradox," American Economic Review Papers and Proceedings, Vol. 80(2): 355-361, (May).

Denison, Edward E. [1989], "Estimates of Productivity Change by Industry, an Evaluation and an Alternative," Brookings Institution, Washington, DC.

Denison, Edward E. [1985], "Trends in American Economic Growth, 1929-1982," Brookings, Washington D. C.

Diewert, W. Erwin and Smith, Ann Marie, [1994], "Productivity Measurement for a Distribution Firm," National Bureau of Economic Research Working Paper No. 4812, (July).

Dixit, Avinash K. and Pindyck [1995], "The Options Approach to Capital Investment," Harvard Business Review, May-June: 105-115.

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, Perdue University.

Dudley, L. and Lasserre, P. [1989], "Information as a Substitute for Inventories," European Economic Review, Vol. 31: 1-21.

Dulberger, Ellen R. [1989], "The Application of Hedonic Model to a Quality Adjusted Price Index for Computer Processors," in Jorgenson and Landau (Ed.), Technology and Capital Formation, MIT Press, Cambridge, MA.

Fisher, Franklin M. and Griliches, Zvi. [1995], "Aggregate Price Indices, New Goods, and Generics," Quarterly Economics, Vol. CX(1): 229-244, (February).

Franke, Richard H. [1987], "Technological Revolution and Productivity Decline: Computer Introduction in the Financial Industry," Technological Forecasting and Social Change, Vol. 31: 143-154.

Fudenberg, D. and Tirole, J. [1985], "Preemption and Rent Equalization in the Adoption of New Technology," Review of Economic Studies, Vol. 52: 383-401.

Gordon, Robert J., [1993], "The Jobless Recovery. Does It Signal a New Era of Productivity-led Growth?", Brookings Papers on Economic Activity, 1993(1): 271-316.

Gordon, Robert J., [1990], "The Measurement of Durable Goods Prices, Chicago: University of Chicago Press," (see especially Chapter 6, Electronic Computers.)

Gordon, Robert J., [1987a], "Productivity, Wages, and Prices Inside and Outside of Manufacturing in the U.S., Japan, and Europe," European Economic Review, April 1987, 31(3), pp.685-739.

Gordon, Robert J., [1987b], "The Postwar Evolution of Computer Prices," National Bureau of Economic Research Working Paper No. 2227, Cambridge, MA.

Gordon, Robert 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, Vol. 2(1).

Griliches, Zvi [1995], "Comments on Measurement Issues in Relating IT Expenditures to Productivity Growth," Economics of Innovation and New Technology, Vol. 3: 317-321.

Griliches, Zvi, [1994], "Productivity, R&D, and Data Constraints," American Economic Review, 84(1), (March).

Griliches, Zvi [1992], "The Search for R&D Spillovers," Scandinavian Economics, Vol. 94, Supplement, pp. 29-47.

Griliches, Zvi and Cockburn, [1994], "Generics and New Goods in Pharmaceutical Price Indexes," American Economic Review, LXXXIV.

Griliches, Zvi. (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, Vol. 33(1): 148-160.

Gurbaxani, V. and Mendelson, H. [1989], "The use of Secondary Data in MIS Research," University of California, Irvine, (March).

Hammer, Michael [1990], "Reengineering Work: Don't Automate, Obliterate," Harvard Business Review, July-August, pp. 104-112.

Hammer, Michael and Champy, James [1993], Reengineering the Corporation, HarperBusiness, New York, NY.

Harris, S. E. and Katz, J. L. [1991], "Organizational Performance and Information Technology Investment Intensity in the Insurance Industry," Organizational Science, Vol. 2(3): 263-296.

Hausman, Jerry A. [1994], "Valuation of New Goods under Perfect and Imperfect Competition," National Bureau of Economic Research Working Paper No. 4970, (December).

Hirshleifer, J. [1971], "The Private and Social Value of Information and the Reward to Inventive Activity," American Economic Review, pp.561-574.

Hitt, Lorin and Brynjolfsson, Erik. [1994], "Three Faces of IT Value: The Theory and Evidence," The Proceedings of the Fifteenth International Conference on Information Systems, (December).

Jensen, Michael [1986], "Agency Costs of Free Cash Flow, Corporate Finance, and Takeovers," American Economic Review Papers and Proceedings, 76: 323-29.

Jensen, Michael [1993], "The Modern Industrial Revolution, Exit, and the Failure of Internal Control Systems," Journal of Finance, Vol. XLVIII(3): 831-880, (July)

Jonscher, C. [1994], "An Economic Study of the Information Technology Revolution," in Allen, Thomas J. and Scott Morton, Michael S. (Ed.), Information Technology and the Corporation of the 1990s: Research Studies, Oxford University Press, pp. 5-42.

Jonscher, C. [1983], "Information Resources and Economic Productivity," Information Economics and Policy, Vol. 1: 13-35.

Jorgenson, Dale W. and Landau, Ralph (Ed.), [1989], Technology and Capital Formation, MIT Press, Cambridge, MA.

Jorgenson, Dale W. and Stiroh, Kevin. [1995], "Computers and Growth," Economics of Innovation and New Technology, Vol. 3: 295-316.

Joskow, Paul L., Schmalensee, Richard, and Tsukanova, Natalia [1994], "Competition Policy in Russia during and after Privatization," Brookings Papers on Economic Activity, Microeconomics: 301-374.

Kambil, A., Henderson, J. C. and Mohsenzadeh, H. [1991], "Strategic Management of Information Technology Investments: An Options Perspective," MIT Center for Information Systems Research Working Paper No. 222, (March)

Kaplan, Robert [1989], "Management Accounting for Advanced Technological Environments," Science, Vol. 245: 819-823, (September).

Katz, Lawrence F. and Krueger, Alan B. [1994], "How Computers Have Changed the Workplace, 1984-1993," Unpublished Paper, Harvard University.

Kemerer, Chris F. and Sosa, G. L. [1991], "Systems Development Risks in Strategic Information Systems," Information and Software Technology, Vol. 33(3): 212-223, (April).

Kraemer, Kenneth L. and Dedrick, Jason [1994], "Payoffs from Investment in Information Technology: Lessons from the Asia-Pacific Region," World Development, Vol. 22(12): 1991-1931.

Kriebel, Charles H. [1989], "Understanding the Strategic Investment in IT," in Lauden, K. C. and Turner, J. A. (Ed.) Information Technology and Management Strategy, Englewood Cliffs, NJ, Prentice Hall.

Krueger, Alan B. [1993], "How Computers Have Changed the Wage Structure: Evidence from Micro-data, 1989-1984," Quarterly Journal of Economics 108(1): 33-60.

Kwon, Myung Joong and Stoneman, Paul [1995], "The Impact of Technology Adoption on Firm Productivity." Economics of Innovation and New Technology, Vol. 3: 219-233.

Landauer, Thomas K. [1995], The Trouble with Computers, The MIT Press, Cambridge, MA.

Lasserre, P. [1988], "Project on the Impact of Information on Productivity," unpublished paper, (September).

Lau, Lawrence J. and Tokutsu, Ichiro [1992], "The Impact of Computer Technology on the Aggregate Productivity of the United States: An Indirect Approach," unpublished paper, Stanford University, (August).

Lichtenberg, Frank R. [1995], "The Output Contributions of Computer Equipment and Personal: A Firm-Level Analysis," Economics of Innovation and New Technology, Vol. 3: 201-217.

Loveman, Gary W. [1994], "An Assessment of the Productivity Impact of Information Technologies," in Allen, Thomas J. and Scott Morton, Michael S. (Ed.), Information Technology and the Corporation of the 1990s: Research Studies, Oxford University Press, pp. 84-110.

Malone, T. and Rockart, J. [1991], "Computers, Networks and the Corporation," Scientific American, Vol. 265(3): 128-136.

Mark, J. A. [1982], "Measuring Productivity in the Service Sector," Monthly Labor Review, (June).

McKersie, Robert. B. and Walton, Richard E. [1991], "Organizational Change," in Scott Morton (Ed.): The Corporation of the 1990s, Oxford University Press, pp. 244-277.

Morrison, Catherine J. and Berndt, Ernst. 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, Vol. 29: 1029-1064.

Nolan/Norton [1988], Management Measures in End User Computing, Nolan Norton Institute, Peat Marwick Special Report.

Noyelle, T. [1990], Skills, Wages, and Productivity in the Service Sector, Boulder, Colorado, Westview Press.

Oliner, Stephen D. and Sichel, Daniel E. [1994], "Computers and Output Growth Revisited: How Big is the Puzzle?" Brookings Papers on Economic Activity, 1994(2): 273-334.

Osterman, P. [1986], "The Impact of Computers on the Employment of Clerks and Managers," Industrial and Labor Relations Review, Vol. 39: 175-186

Panko, R. R. [1991], "Is Office Productivity Stagnant?" MIS Quarterly, pp. 109-203, (June).

Parsons, D. J., Gotlieb, C. C. and Denny, M. [1990], "Productivity and Computers in Canadian Banking," University of Toronto Dept. of Economics Working Paper No. 9012, (June).

Porat, M. [1977], The Information Economy: Definition and Measurement, US 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, Stephen S. [1991], "Services under Siege: the Restructuring Imperative," Harvard Business Review 39(2): 82-92, (September-October).

Roach, Stephen S. [1989a], "Pitfalls of the New Assembly Line: Can Service Learn From Manufacturing?" Morgan Stanley Special Economic Study, New York, (June 22).

Roach, Stephen S. [1989b], "America's White-Collar Productivity Dilemma," Manufacturing Engineering , August , pp. 104.

Roach, Stephen S. [1987], "America's Technology Dilemma: A Profile of the Information Economy," Morgan Stanley Special Economic Study, (April).

Romer, Paul M. [1986], "Increasing Returns and Long-Run Growth," Journal of Political Economy, Vol. 94(5):1002-37

Romer, Paul M. [1987], "Crazy Explanations for the Productivity Slowdown," in Stanley Fisher (Ed.), NBER Macroeconomics Annual: 1987, MIT Press, Cambridge, MA.

Samuelson, P., Davis, R., Kapor, M. D., and Reichman, J. H. [1994], "A Manifesto Concerning the Legal Protection of Computer Programs," Columbia Law Review, Vol. 94.

Scherer, F. [1980], Industrial Market Structure and Economic Performance, Rand-McNally, Chicago, IL.

Schneider, K. [1987], "Services Hurt by Technology: Productivity is Declining," The New York Times, June 29: D1, D6.

Scott Morton, Michael S. (Ed.) [1991], The Corporation of the 1990s: Information Technology and Organizational Transformation, Oxford University Press.

Sichel, Daniel E. [1995], "The Computer Paradox and the Productivity Slowdown: Is a Growing Unmeasurable Sector the Culprit?" The Brookings Institution Working Paper, (April).

Siegel, Donald [1994], "The Impact of Computers on Manufacturing Productivity Growth: A Multiple-Indicators, Multiple-Causes Approach," SUNY at Stony Brook Working Paper, (May).

Siegel, Donald and Griliches, Zvi [1992], "Purchased Services, Outsourcing, Computers, and Productivity in Manufacturing," in Griliches et al. (Ed.), Output Measurement in the Service Sectors, University of Chicago Press.

Snow, C. P. [1966], "Government Science and Public Policy," Science, Vol. 151: 650-653.

Simon, Herbert A., [1987], "The Steam Engine and the Computer: What Makes Technology Revolutionary?", EDUCOM Bulletin, Vol. 22(1): 2-5, (Spring).

Stabell, C. B. [1982], "Office Productivity: A Microeconomic Framework for Empirical Research," in Office: Technology and People, Vol. 1: 91-106.

Stein, Jeremy C. [1989], "Efficient Capital Markets, Inefficient Firms: A Model of Myopic Corporate Behavior," Quarterly Journal of Economics, (November).

Steiner, T. D. and Teixeira, D. B. [1991], Technology and Business: Creating Value and Destroying Profits, Dow Jones Irwin, Homewood, IL.

Strassmann, P. A. [1990], The Business Value of Computers: An Executive's Guide. New Canaan, CT, Information Economics Press.

Strassmann, P. A. [1985], Information Payoff: The Transformation of Work in the Electronic Age, Free Press, New York, NY.

Thurow, Lester [1987], "Economic Paradigms and Slow American Productivity Growth," Eastern Economic Journal, Vol. 13: 333-343.

Tirole, Jean [1988], The Theory of Industrial Organization, MIT Press, Cambridge, MA.

Trajtenberg, Manuel [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, Peter [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, Diane. D. [1995], "IT Investment and Its Productivity Effects: An Organizational Sociologist's Perspective on Directions for Future Research." Economics of Innovation and New Technology, Vol. 3: 235-251.

Wong, Poh-Kam [1994], "Productivity Impact of IT Investment in Singapore," in Proceedings of the fifteenth International Conference on Information Systems, (December).

Yamamoto [1991], "The Justification of Information Technology Investments," MIT Sloan School Master's Thesis.

Zachary, G. P. [1991], "Computer Data Overload Limits Productivity Gains," Wall Street Journal, November 11, pp. B1.